(Future) Collider Magnets

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CAS School on Normal and Superconducting Magnets
19 November – 1 December, 2023, Sankt Poelten, Austria

1983
–2023
years

The CERN Accelerator School

Outline

- HEP landscape
  - The need for high fields
  - The need for energy
  - The need for economics
- Case study: the Muon Collider
- HEP – For what ?
- Summary

Note(-1): This talk is based on the work of many
Note(0): this is not an academic lecture

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Hall of Fame of SC colliders

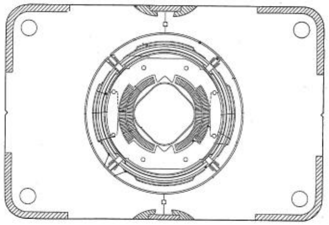
		Tevatron	HERA	RHIC	LHC
Maximum energy	(GeV)	980	920(1)	250(2) 100/n(3)	7000
Injection energy	(GeV)	151	45	12	450
Ring length	(km)	6.3	6.3	3.8	26.7
Dipole field	(T)	4.3	5.0	3.5	8.3
Aperture	(mm)	76	75	80	56
Configuration		Single bore	Single bore	Single bore	Twin bore
Operating temperature	(K)	4.2	4.5	4.3-4.6	1.9
First beam		7-1983	4-1991	6-2000	9-2008

(1) energy of the proton beam, colliding with the 27.5 GeV electron beam

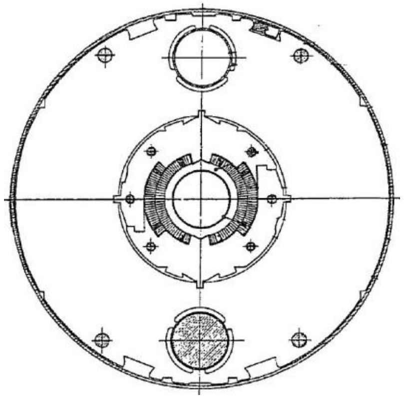
(2) energy for proton beams

(3) energy per nucleon, for ion beams (Au)

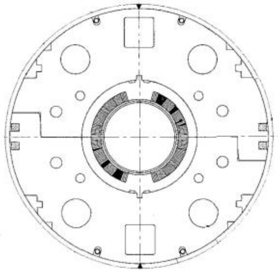
Dipoles cross sections



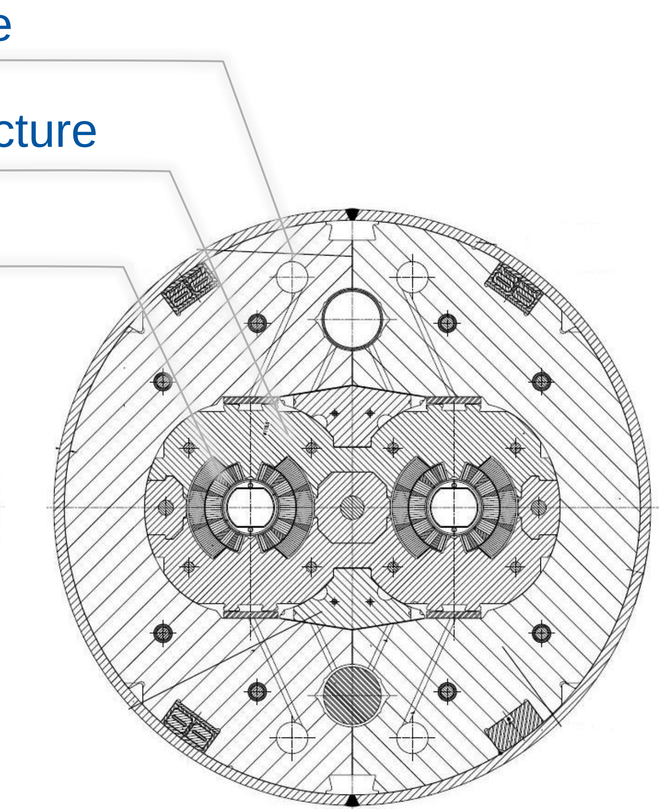
Tevatron
Bore: 76 mm
Field: 4.3 T



HERA
Bore: 75 mm
Field: 5.0 T

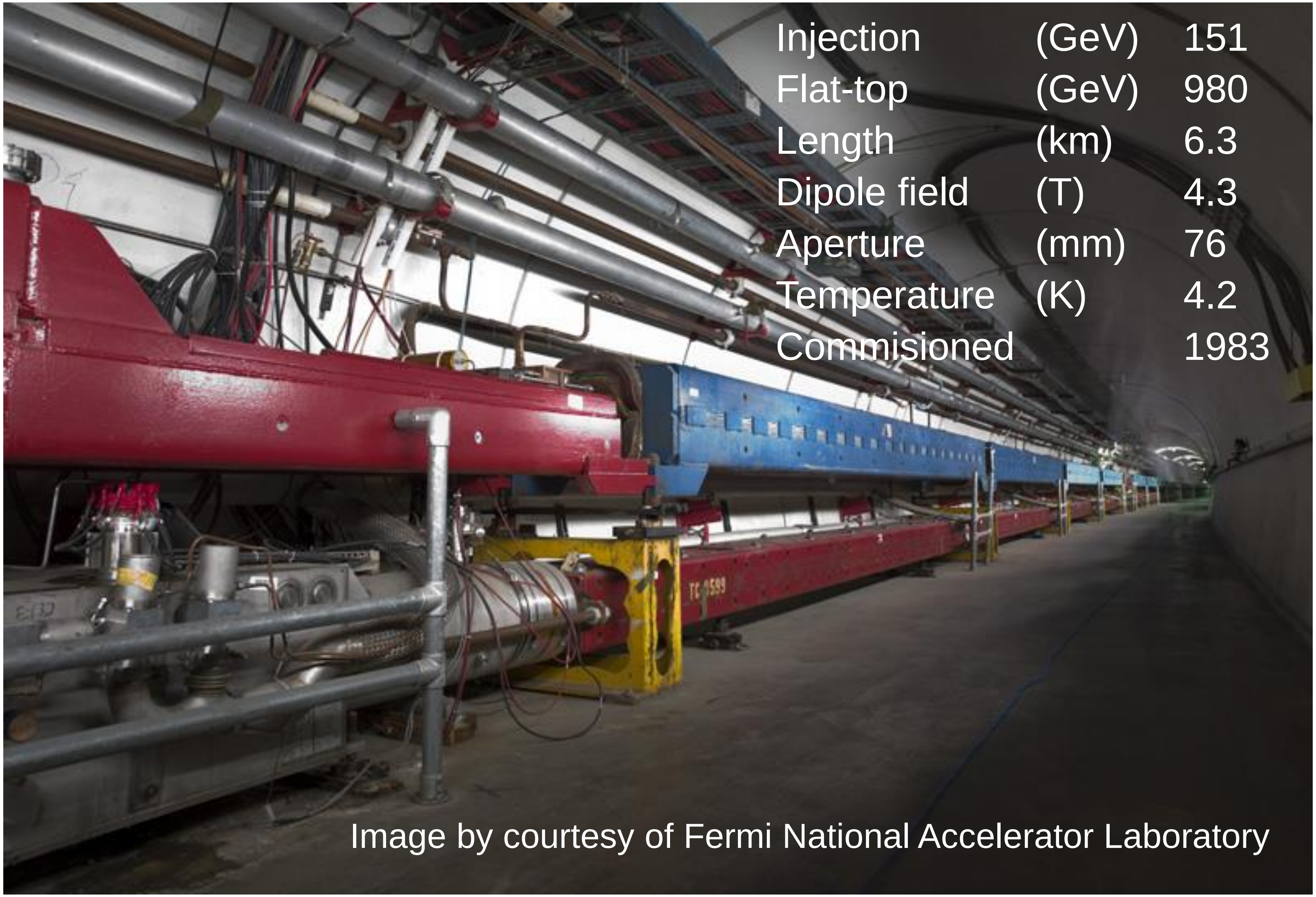


RHIC
Bore: 80 mm
Field: 3.5 T



LHC
Bore: 56 mm
Field: 8.3 T

Tevatron



Injection	(GeV)	151
Flat-top	(GeV)	980
Length	(km)	6.3
Dipole field	(T)	4.3
Aperture	(mm)	76
Temperature	(K)	4.2
Commisioned		1983

Image by courtesy of Fermi National Accelerator Laboratory

HERA

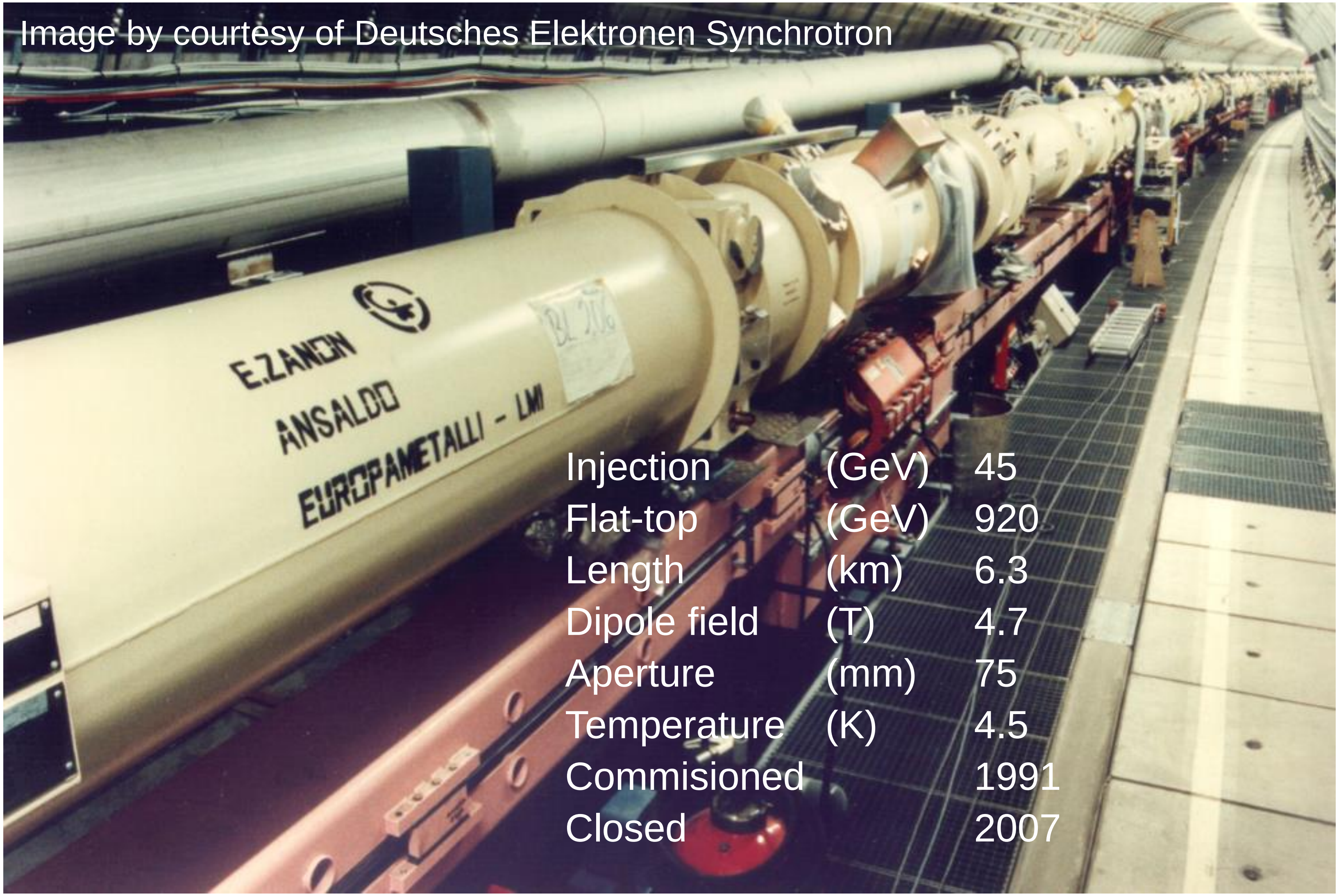


Image by courtesy of Deutsches Elektronen Synchrotron

Injection	(GeV)	45
Flat-top	(GeV)	920
Length	(km)	6.3
Dipole field	(T)	4.7
Aperture	(mm)	75
Temperature	(K)	4.5
Commisioned		1991
Closed		2007

RHIC

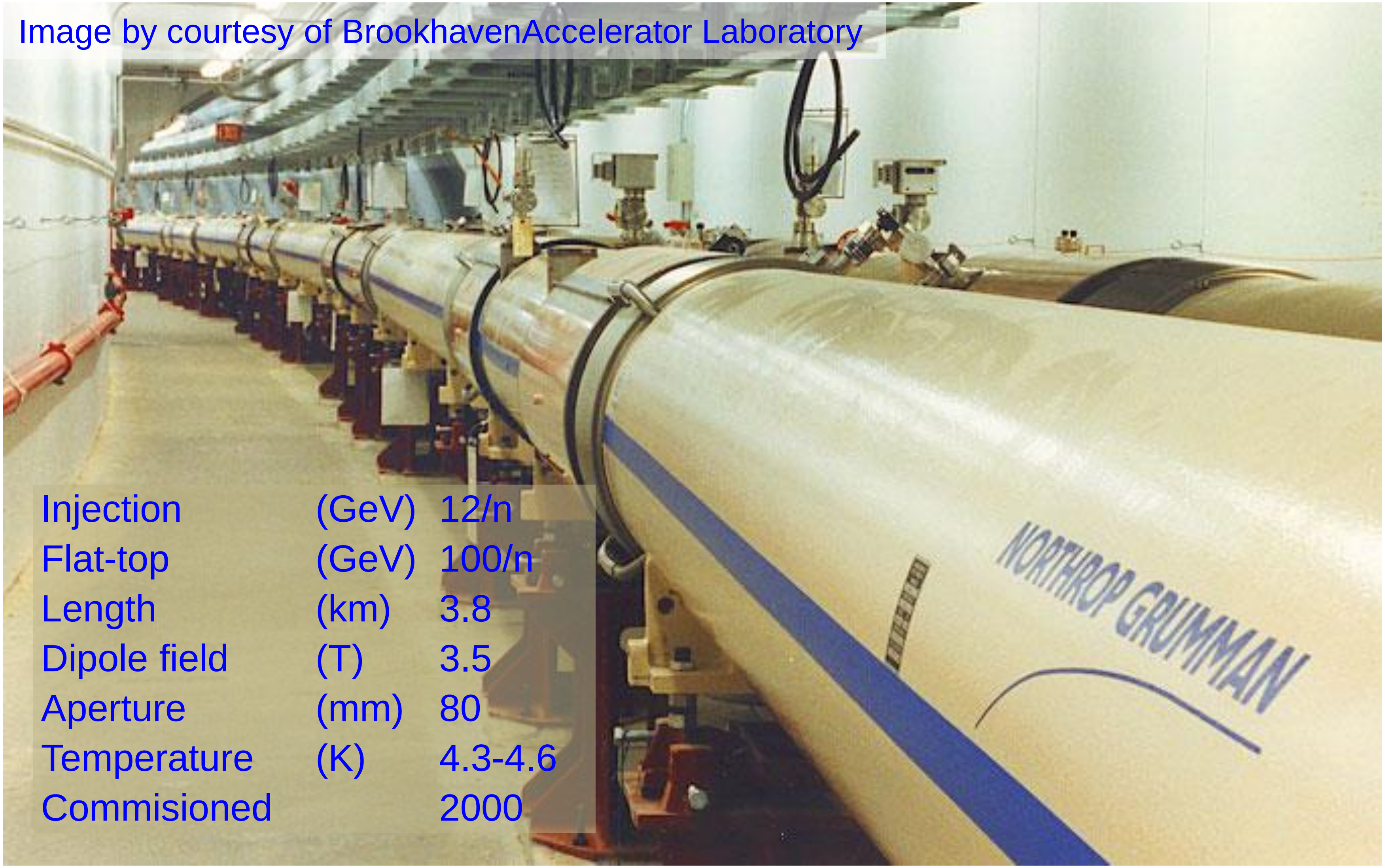
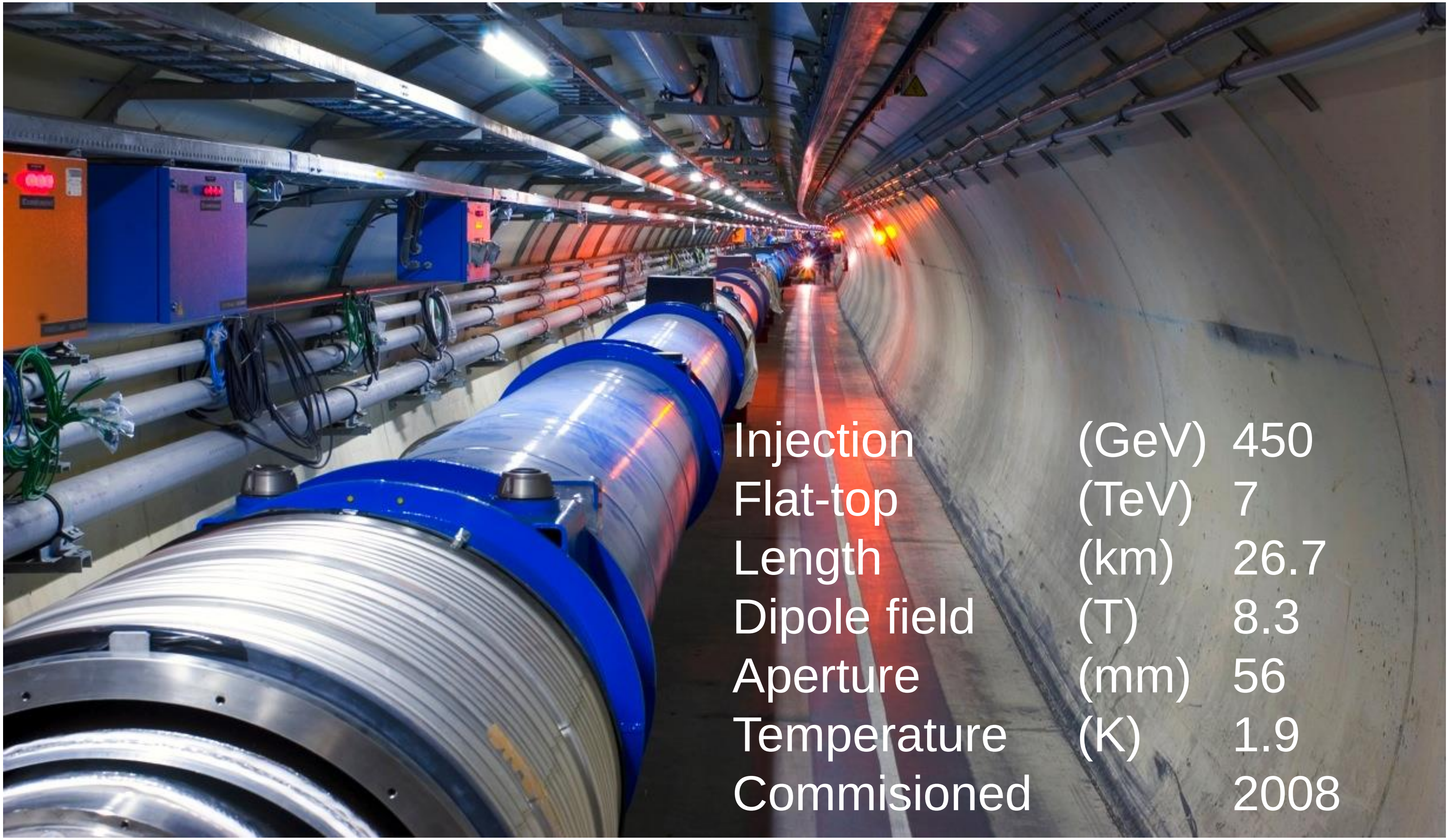


Image by courtesy of BrookhavenAccelerator Laboratory

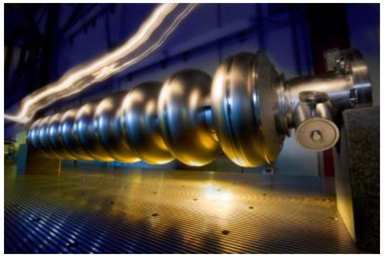
Injection	(GeV)	12/n
Flat-top	(GeV)	100/n
Length	(km)	3.8
Dipole field	(T)	3.5
Aperture	(mm)	80
Temperature	(K)	4.3-4.6
Commisioned		2000

LHC

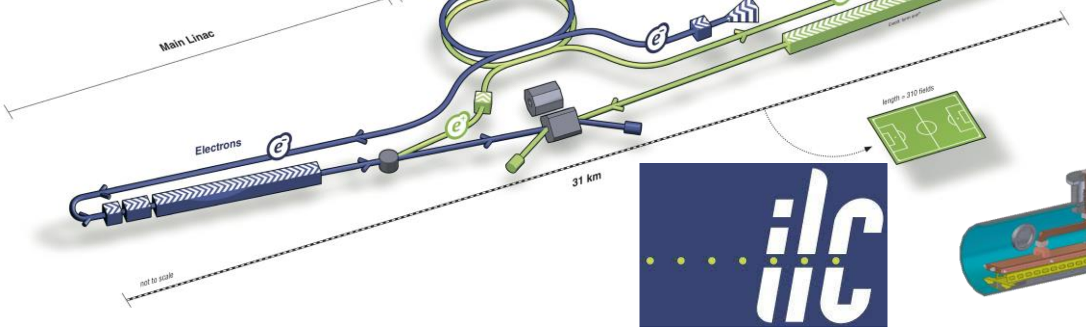


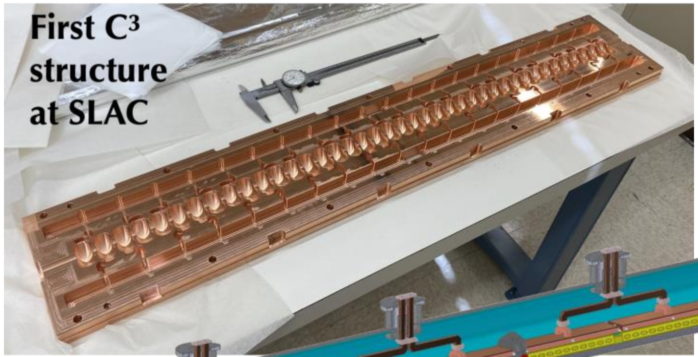
Injection	(GeV)	450
Flat-top	(TeV)	7
Length	(km)	26.7
Dipole field	(T)	8.3
Aperture	(mm)	56
Temperature	(K)	1.9
Commisioned		2008

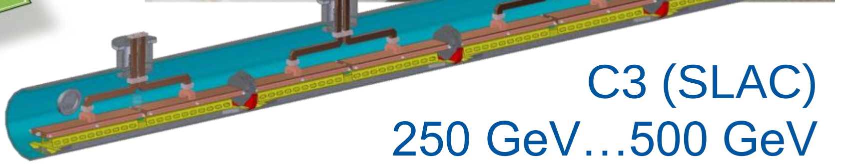
HEP Landscape - Linear Colliders



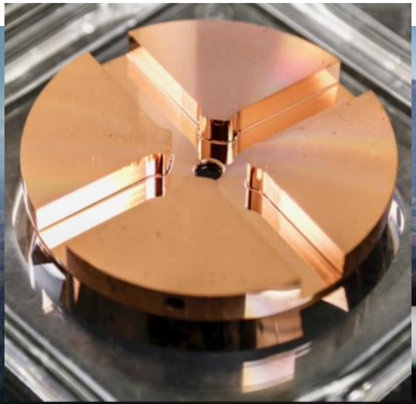
ILC
250 GeV…1 TeV
> 2035





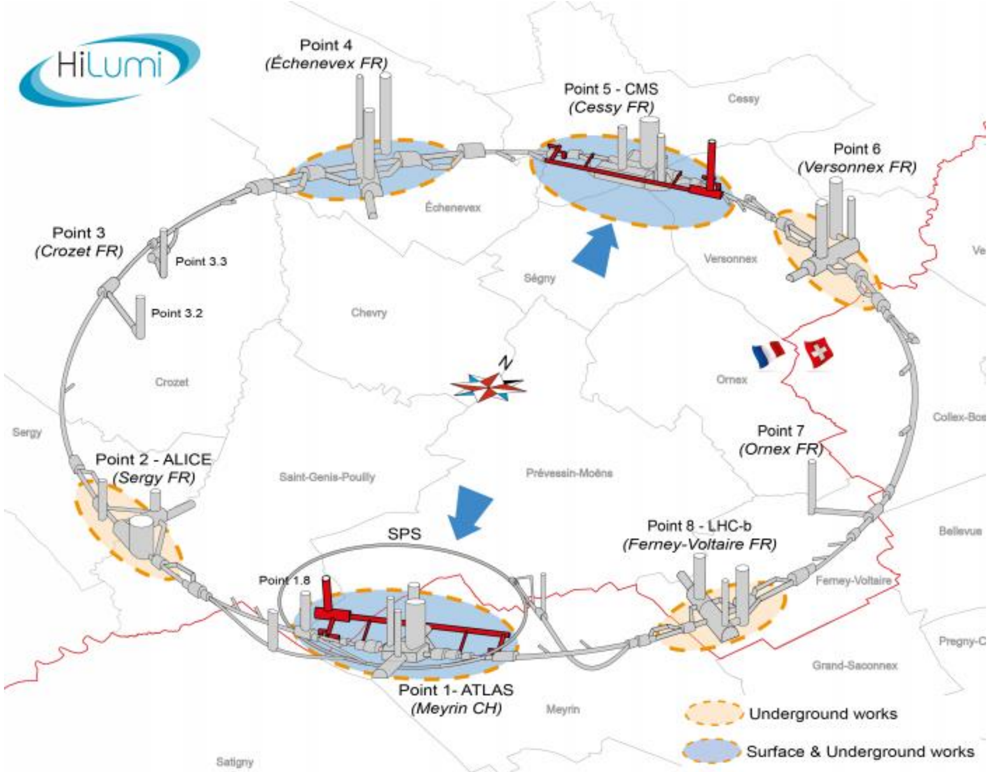


C3 (SLAC)
250 GeV…500 GeV
> 2040

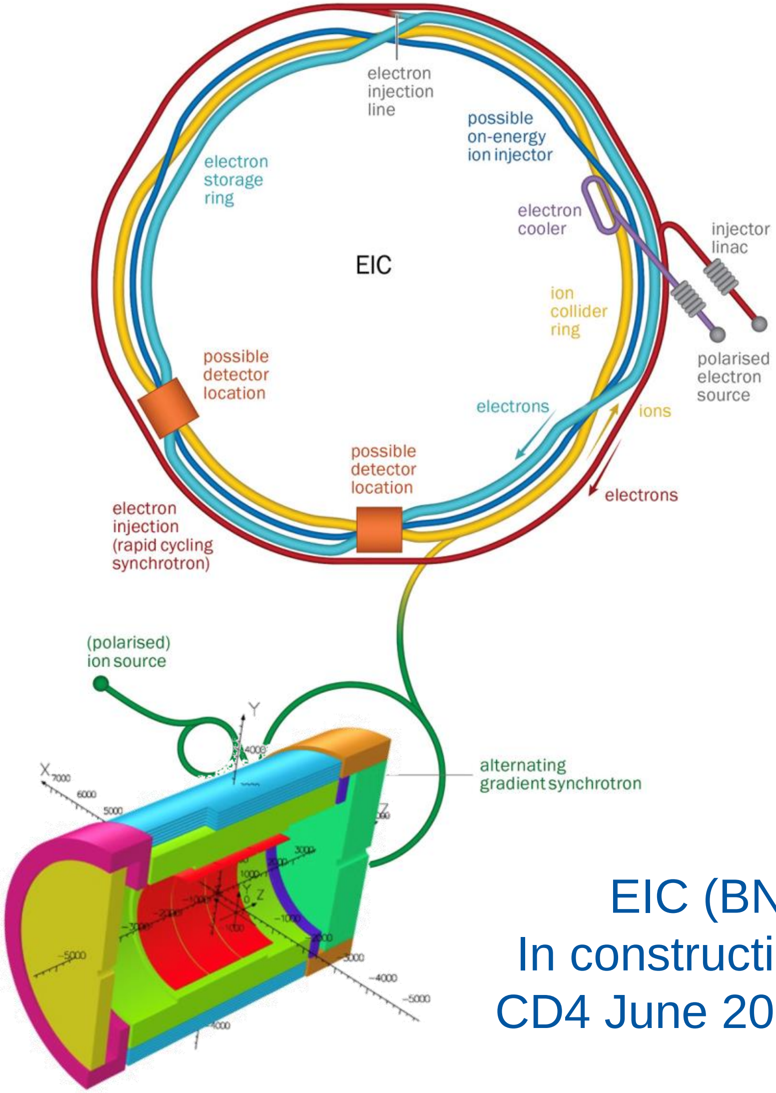


CLIC (CERN)
500 GeV…3TeV
> 2035

HEP Landscape - Circular Colliders

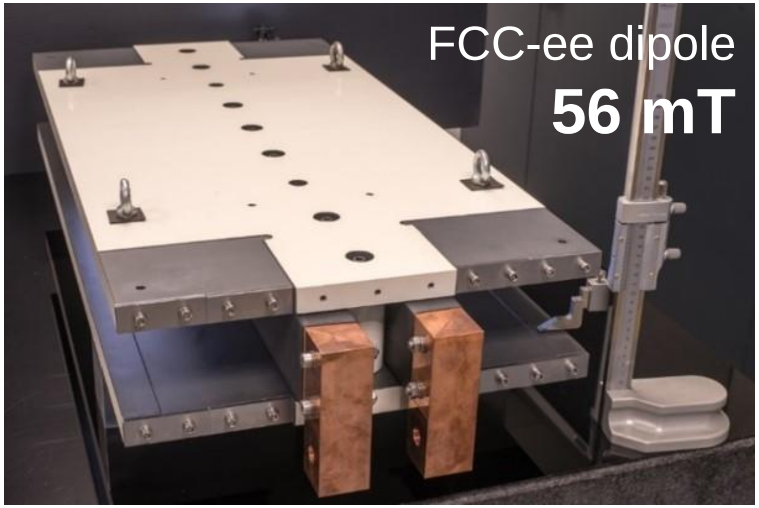


HL-LHC (CERN)
Installation 2026-2028
Commissioning 2029



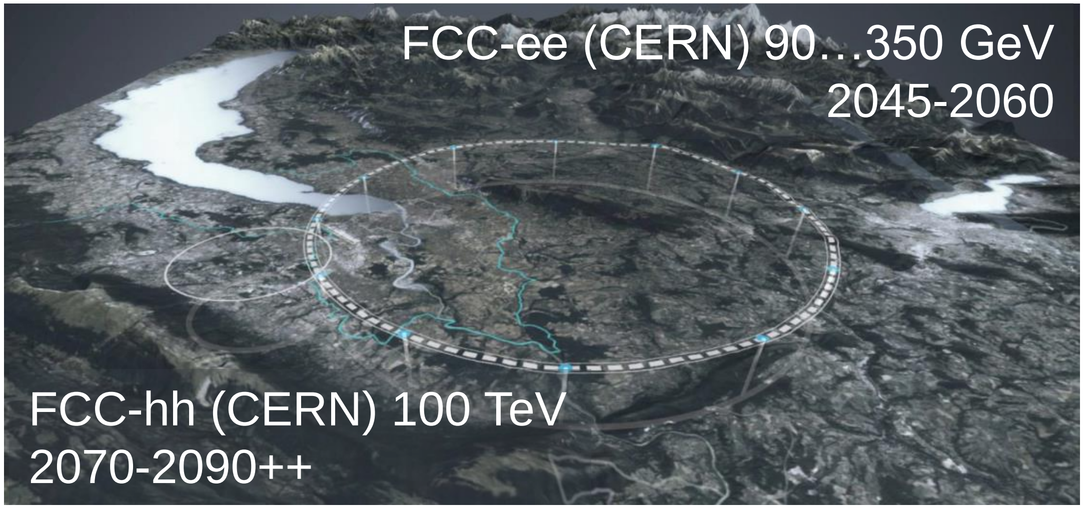
EIC (BNL)
In construction
CD4 June 2030

HEP Landscape - Circular Colliders



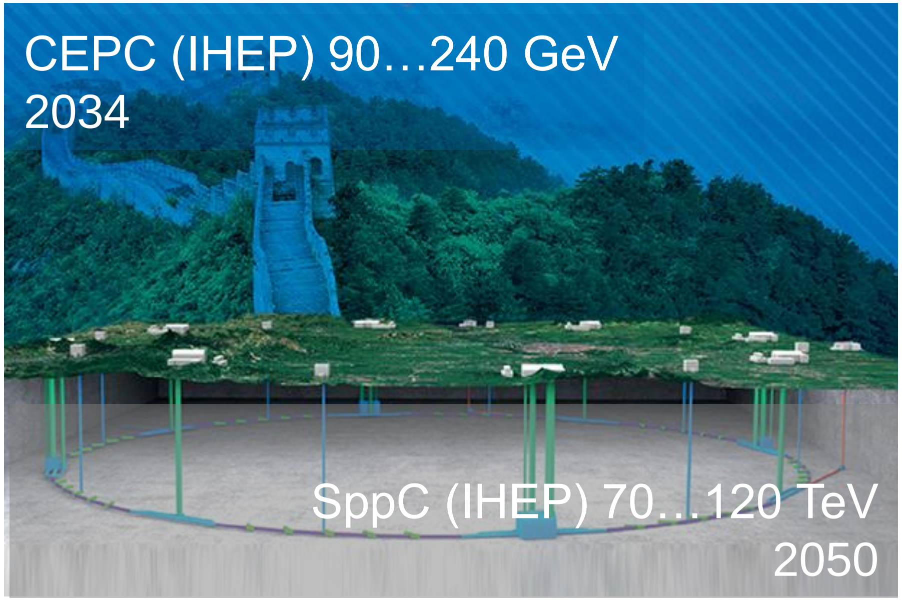
FCC-ee dipole

56 mT



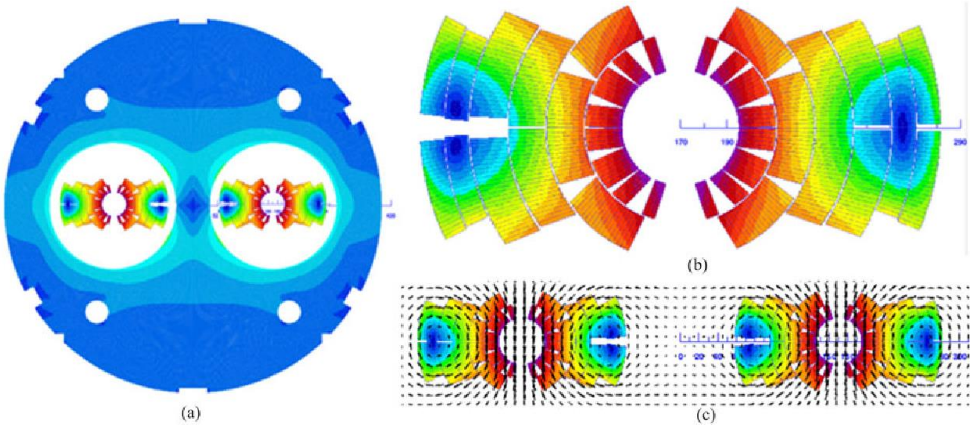
FCC-ee (CERN) 90…350 GeV
2045-2060

FCC-hh (CERN) 100 TeV
2070-2090++



CEPC (IHEP) 90…240 GeV
2034

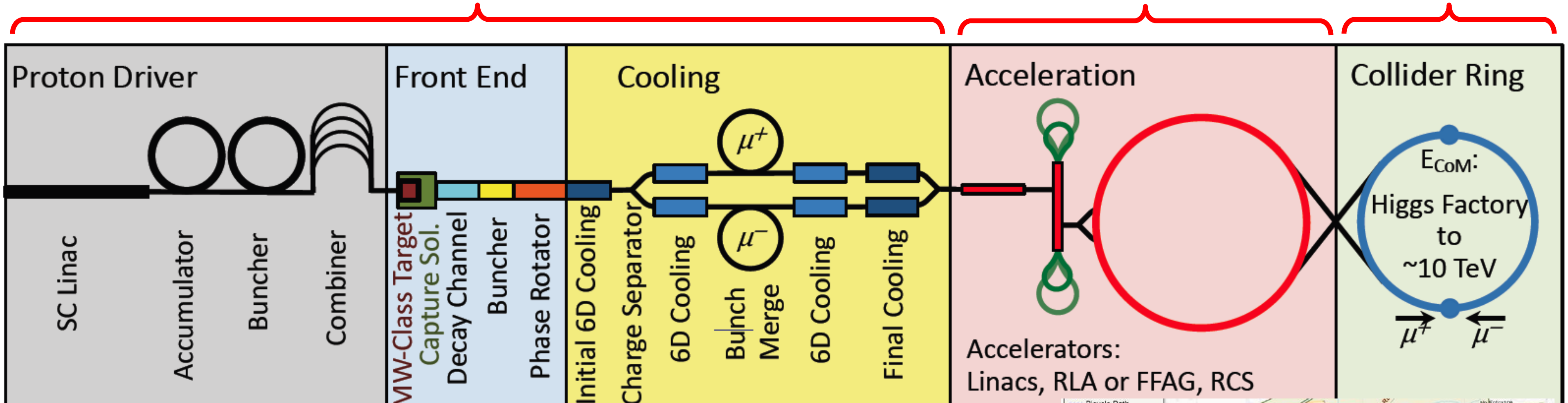
SppC (IHEP) 70…120 TeV
2050



Design of a **20 T** SppC dipole

HEP Landscape - Circular Colliders

Produce a low emittance beam… accelerate … collide !

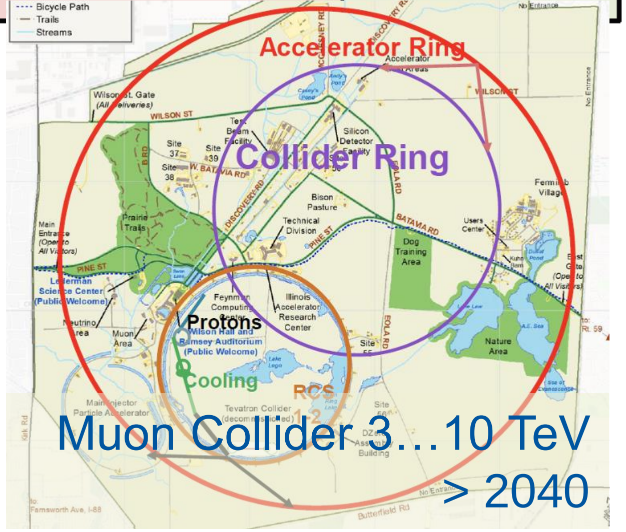


Produce a short, intense proton bunch…

protons hit a target and produce pions which decay into muons - muons are captured…

… muons are cooled by ionization cooling in matter

Credits to US-DOE
Muon Accelerator program (MAP)

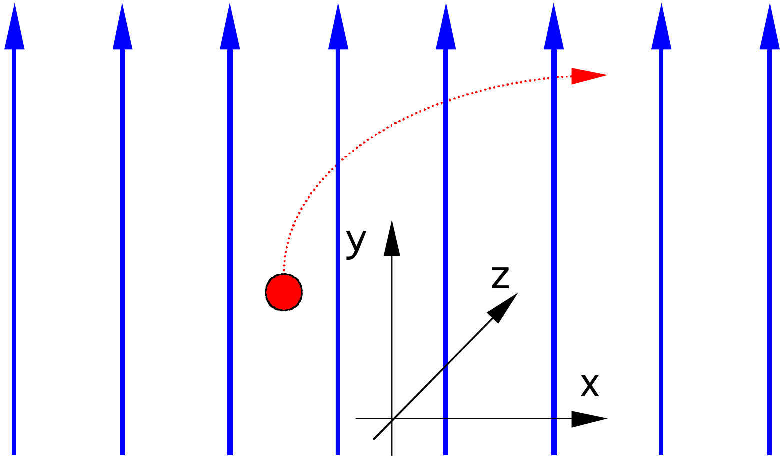


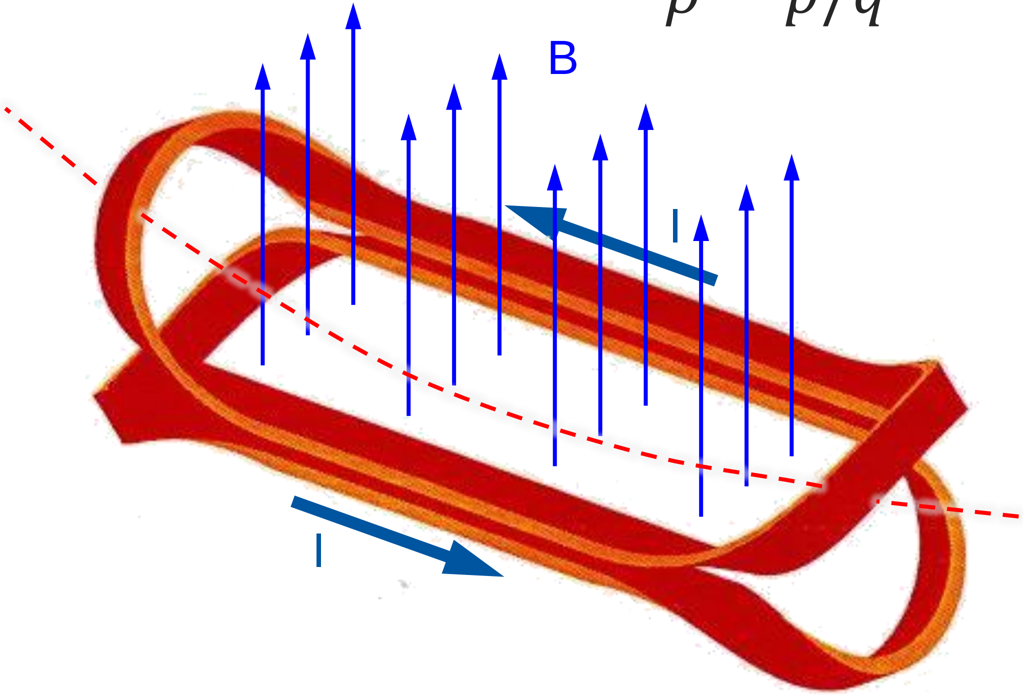
Muon Collider 3…10 TeV
> 2040

Bending (dipole)

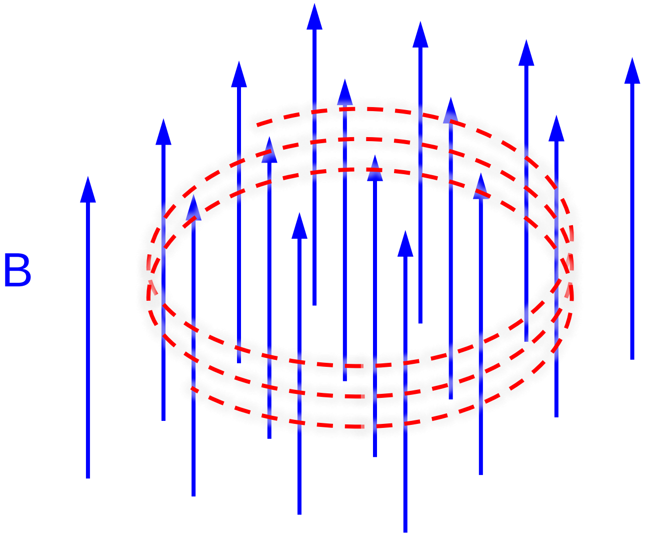
Lorentz force on a moving charged particle: $\vec{F}_L = q\vec{v} \times \vec{B}$

Beam curvature: $\frac{1}{\rho} \approx \frac{B}{p/q}$





Need focusing !



The particle trajectory is a circle only in ideal conditions

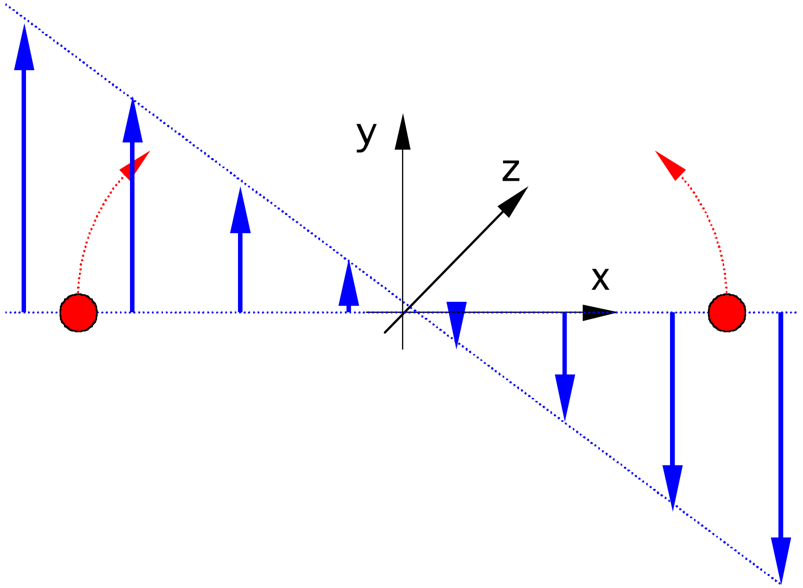
Focusing (quadrupole)

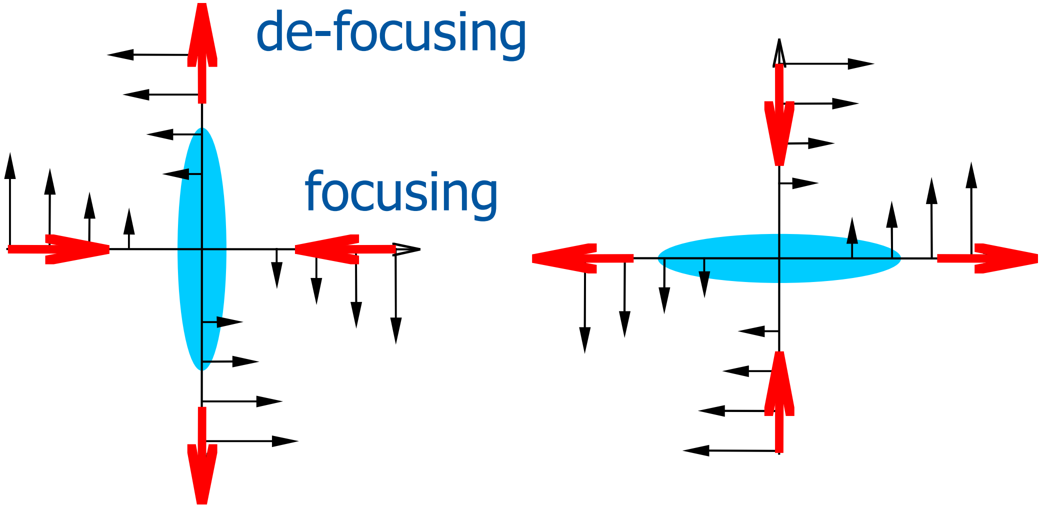
A moving charged particle experiences a force proportional to the distance from the field axis:

$$|F_L| = kx$$

Focusing strength:

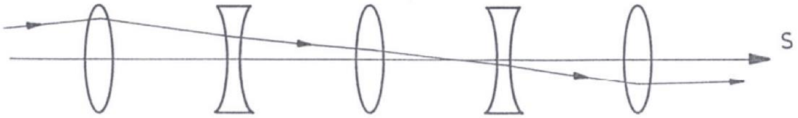
$$\frac{1}{f} \approx \frac{G l_Q}{p/q}$$




de-focusing

focusing

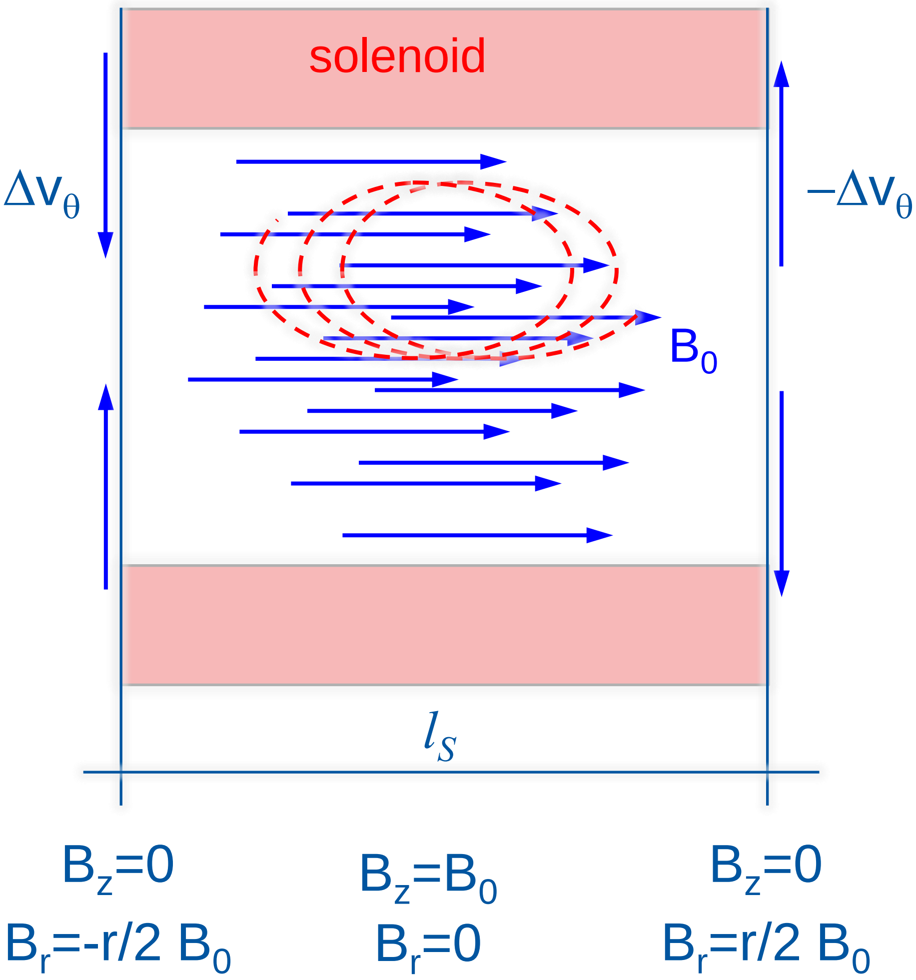
A quadrupole that is focusing in one plane is forcibly de-focusing in the other plane (rot(**B**)=0)

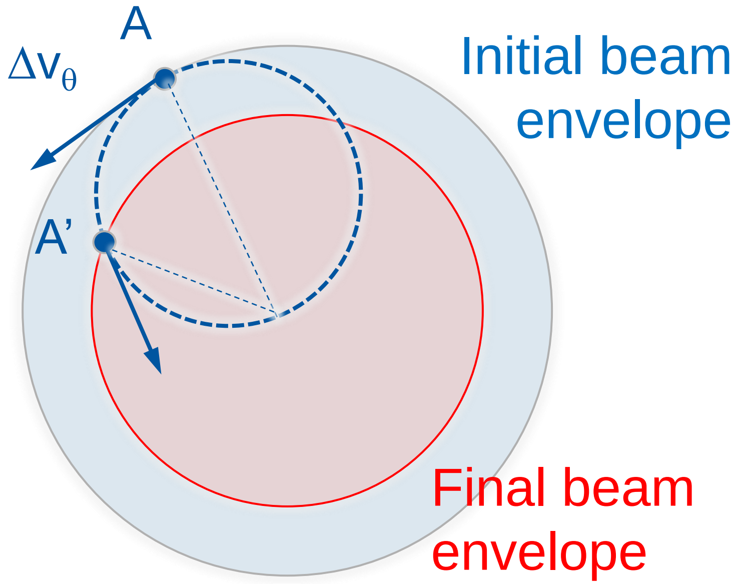


Alternating gradients (FODO cells)

Focusing (solenoid)

Hard edge solenoid, *thin lens*





Focussing strength: $$\frac{1}{f} \approx \frac{1}{2}\frac{B_0^2 l_S}{(p/q)^2}$$

Solenoids are generally **used only at low p/q** *BUT they can focus both charges at the same time*

Outline

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    - The need for high fields
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- Case study: the Muon Collider
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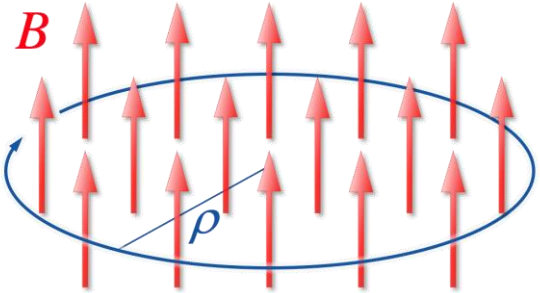
High fields

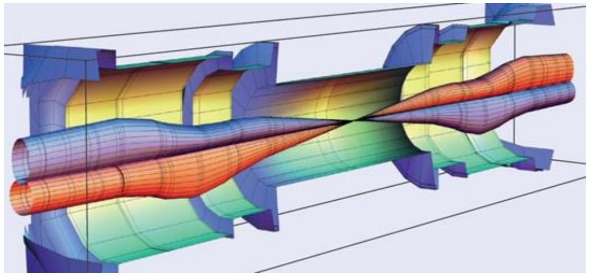


Dipole (example of main bend)

$$E[GeV] = 0.3\,q\,\rho[m]\,\boxed{B[T]}$$

Design for the largest feasible and economic B to reduce the accelerator radius (civil engineering cost)

Quadrupole (example of *final focus*)



Beam size at the quadrupole $\sigma = \frac{\varepsilon}{\gamma}\frac{f}{\sigma^*}$ Emittance, Focal length, Lorentz factor, Beam size at the IP

$$f[m] = \frac{E[GeV]}{0.3\,q\,Gl_Q[T]}$$

Integrated gradient

Peak coil field $B \approx \sigma G$

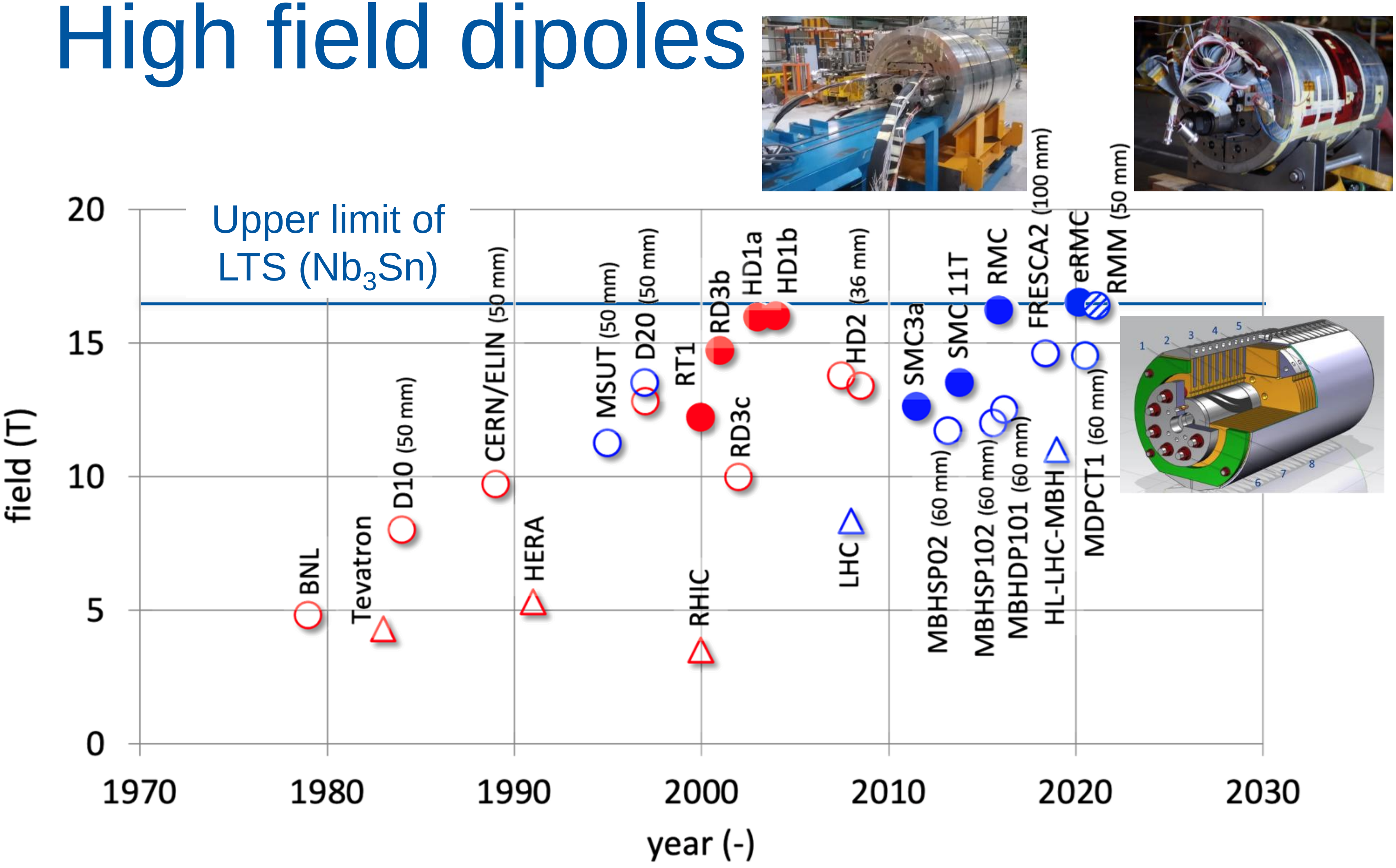
$$\boxed{Bl_Q} \approx \frac{1}{\sigma^*}$$

Beam size at the IP

Design for the largest feasible and economic integrated field to achieve the smallest beam size at the IP

Superconducting accelerator magnets !

High field dipoles



Note(1): HTS is the only path beyond 16 T

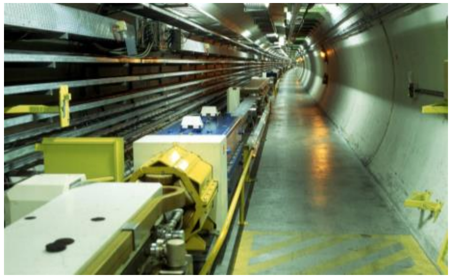
Numerical examples

$$\frac{1}{\rho} \approx \frac{B}{p/q}$$

- Bending radius: $\boxed{\rho[m] = \frac{E[GeV]}{0.3qB[T]}}$ *Fundamental equation*

Hadron example (LHC): a 7 TeV p^+ beam is bent by a 8.33 T field on a radius of 2801 m (L=17.6 km)

Lepton example 1: to bend a 125 GeV e^- beam (Higgs) in the LHC tunnel, i.e. with a radius of 2801 m, one would need a field of 0.15 T



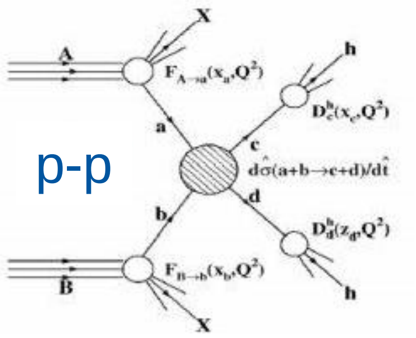
Lepton example 2: the same 125 GeV e^- beam would be bent by the LHC field of 8.33 T on a radius of 50 m (L=314 m !!!)

Collider Choices

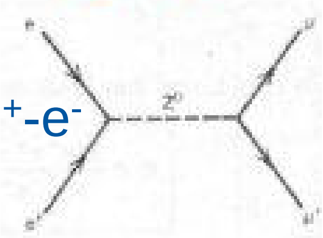
- Hadron collisions: compound particles
  - LHC collides 13.6 TeV protons
  - Protons are mix of quarks, anti-quarks and gluons
  - **Very complex to extract physics**

- Lepton collisions: elementary particles
  - LEP reached 0.205 TeV with electron-positron collisions
  - Clean events, easy to extract physics
  - **Lepton collisions ⇒ precision measurements**

p-p

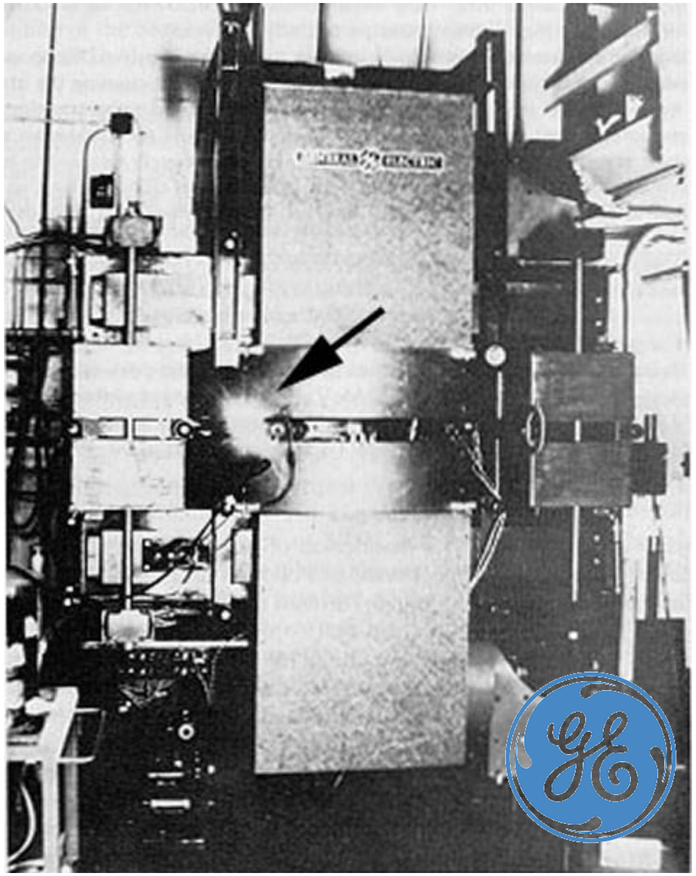


e^+-e^-



So, why not building a high energy lepton collider ?

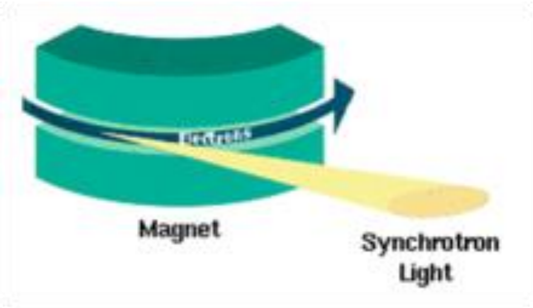
A piece of history



"On April 24 [1947], Langmuir and I [H. Pollock] were running the machine [...] Some intermittent sparking had occurred and ***we asked the technician*** *to observe with a mirror around the protective concrete wall. He immediately signaled to turn off the synchrotron as "he saw an arc in the tube." The vacuum was still excellent, so Langmuir and I came to the end of the wall and observed. At first we thought it might be due to Cherenkov radiation, but it soon became clearer that we were seeing Ivanenko and Pomeranchuk [Synchrotron] radiation."*

Energy loss per turn

- Particle beams emit synchrotron radiation as they are bent on their trajectory
- This appears as an energy loss that needs to be compensated by the RF cavities



Beam energy *Fundamental equation*

Energy loss per turn

$$\delta E[keV] = 88.5\frac{E^4[GeV]}{m^4}\frac{1}{\rho[m]}$$

Bending radius

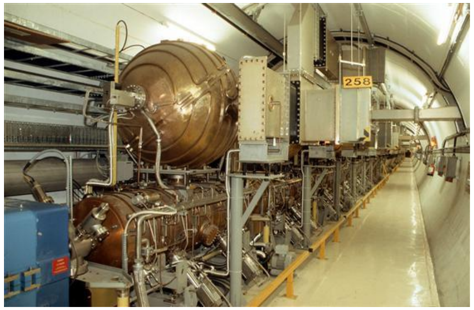
Mass ratio to electrons

- The energy loss per turn grows dramatically with energy, and with the inverse of the particle mass (4th power)

Numerical examples

- Energy loss per turn $\delta E[keV] = 88.5 \frac{E^4[GeV]}{m^4} \frac{1}{\rho[m]}$

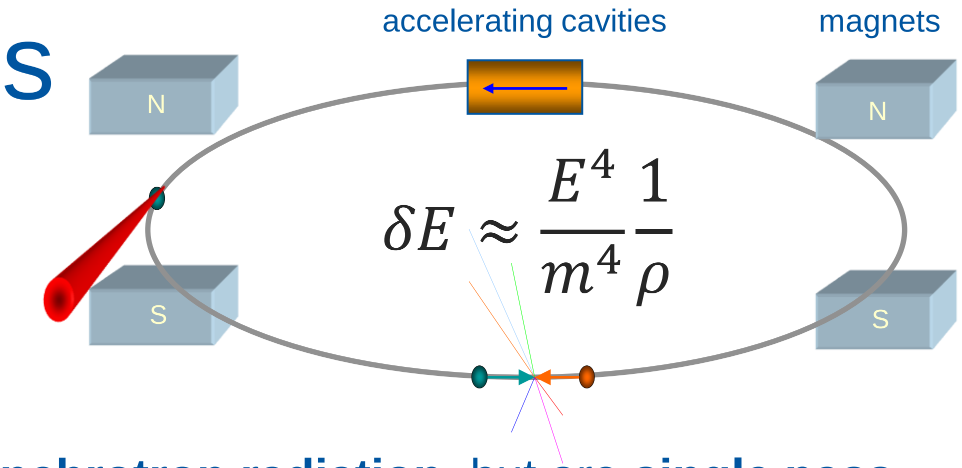
Hadron example (LHC): a p$^+$ (m = 1840) of 7 TeV energy bent on a radius of 2801 m, looses a total of δE = 6.6 keV per turn (0.1 ppb/turn)



Lepton example 1 (LEP): a e$^-$ (m = 1) with 104.5 GeV energy bent on a radius of 2801 m, looses a total of δE = 3.77 GeV per turn (3.6 %/turn !!!)

Lepton example (Muon Collider): a muon (m = 206.8) with 5 TeV energy bent on a radius of 1667 m, looses a total of δE = 18 MeV per turn (3.6 ppm/turn)

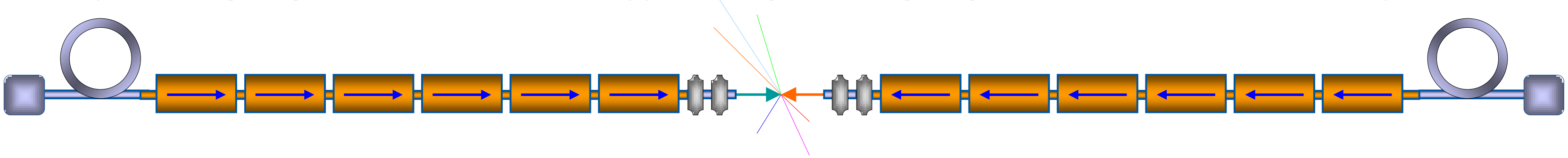
Leptons vs. hadrons



$$\delta E \approx \frac{E^4}{m^4}\frac{1}{\rho}$$

Electron-positron rings (*multi-pass colliders*) are **limited by synchrotron radiation**

Electron-positron linear colliders **avoid synchrotron radiation**, but are **single pass**
Typically cost proportional to energy and power proportional to luminosity,



This is why energy frontier is presently probed by **proton rings**

Novel approach: the **muon collider**
Large mass suppresses synchrotron radiation => circular collider, **multi-pass**
Fundamental particle yields clean collisions, requires less energy than protons
But lifetime at rest only 2.2 μs (increases with energy, approx 100 ms at 3…5 TeV)

The **muon collider** is part of the EU Accelerator R&D Roadmap

Courtesy of D. Schulte

e^-: 0.511 MeV
μ: 106 MeV
p^+: 938 MeV

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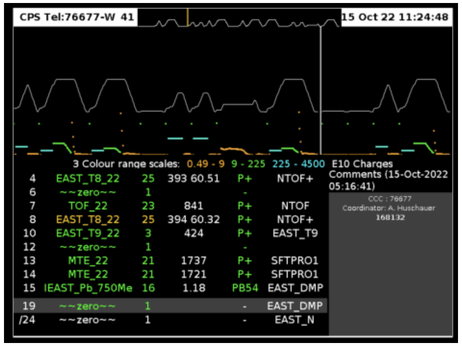
The need for energy

- CERN uses today **1.3 TWh** per year of operation, with peak power consumption of **200 MW** (running accelerators and experiments), dropping to **80 MW** in winter (technical stop period)
- Electric power is drawn directly from the French 400 kV distribution, and presently supplied under agreed conditions and cost
- **Supply cost, chain and risk** are obvious concerns for the present and future of the laboratory



CPS Tel:76677-W 41 15 Oct 22 11:24:48

3 Colour range scales: 0.49 - 9 9 - 225 225 - 4500 E10 Charges

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6	~~zero~~	1		-	
7	TOF_22	23	841	P+	NTOF
8	EAST_T8_22	25	394 60.32	P+	NTOF+
10	EAST_T9_22	3	424	P+	EAST_T9
12	~~zero~~	1		-	
13	MTE_22	21	1737	P+	SFTPRO1
14	MTE_22	21	1721	P+	SFTPRO1
15	IEAST_Pb_750Me	16	1.18	PB54	EAST_DMP
19	~~zero~~	1		-	EAST_DMP
/24	~~zero~~	1		-	EAST_N

Comments (15-Oct-2022 05:16:41)

CCC : 76677
Coordinator: A. Huschauer
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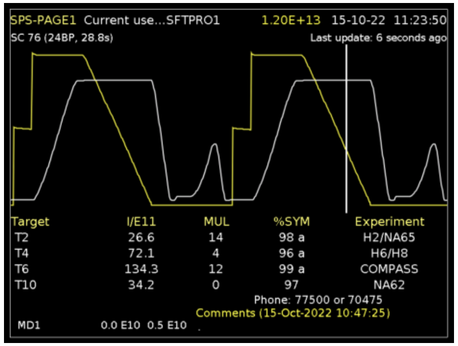

SPS-PAGE1 Current use...SFTPRO1 1.20E+13 15-10-22 11:23:50

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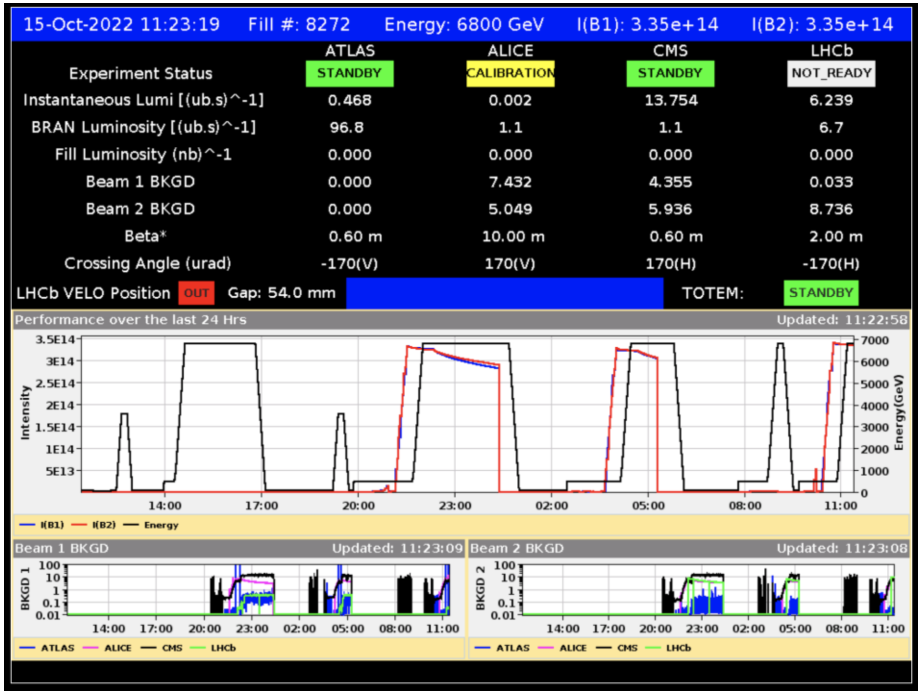
Target	I/E11	MUL	%SYM	Experiment
T2	26.6	14	98 a	H2/NA65
T4	72.1	4	96 a	H6/H8
T6	134.3	12	99 a	COMPASS
T10	34.2	0	97	NA62

Phone: 77500 or 70475

Comments (15-Oct-2022 10:47:25)

MD1 0.0 E10 0.5 E10



15-Oct-2022 11:23:19 Fill #: 8272 Energy: 6800 GeV I(B1): 3.35e+14 I(B2): 3.35e+14

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	CALIBRATION	STANDBY	NOT_READY
Instantaneous Lumi [(ub.s)^-1]	0.468	0.002	13.754	6.239
BRAN Luminosity [(ub.s)^-1]	96.8	1.1	1.1	6.7
Fill Luminosity (nb)^-1	0.000	0.000	0.000	0.000
Beam 1 BKGD	0.000	7.432	4.355	0.033
Beam 2 BKGD	0.000	5.049	5.936	8.736
Beta*	0.60 m	10.00 m	0.60 m	2.00 m
Crossing Angle (urad)	-170(V)	170(V)	170(H)	-170(H)

LHCb VELO Position OUT Gap: 54.0 mm TOTEM: STANDBY

Performance over the last 24 Hrs Updated: 11:22:58

Beam 1 BKGD Updated: 11:23:09

Beam 2 BKGD Updated: 11:23:08

16 JUIN 2022 **Publications** Briefings de l'Ifri

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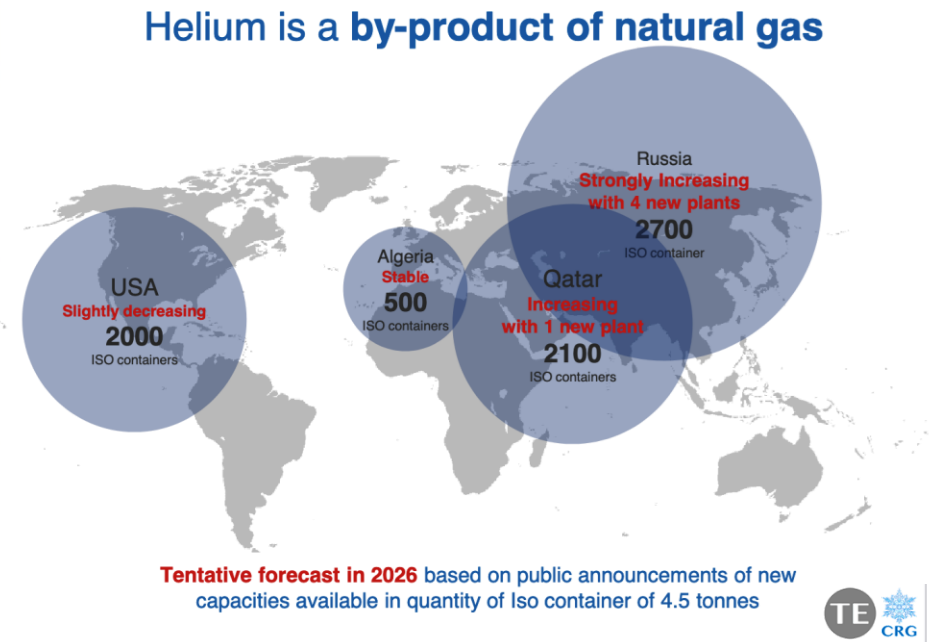
Aurélien REYS, Vincent BOS

Hélium : les nouvelles géographies d'une ressource critique

Briefings de l'Ifri, 16 juin 2022

Helium is a **by-product of natural gas**



Tentative forecast in 2026 based on public announcements of new capacities available in quantity of Iso container of 4.5 tonnes

Future helium **supply is limited** and entails a substantial economical and availability **risk**

Consequences

Current situation

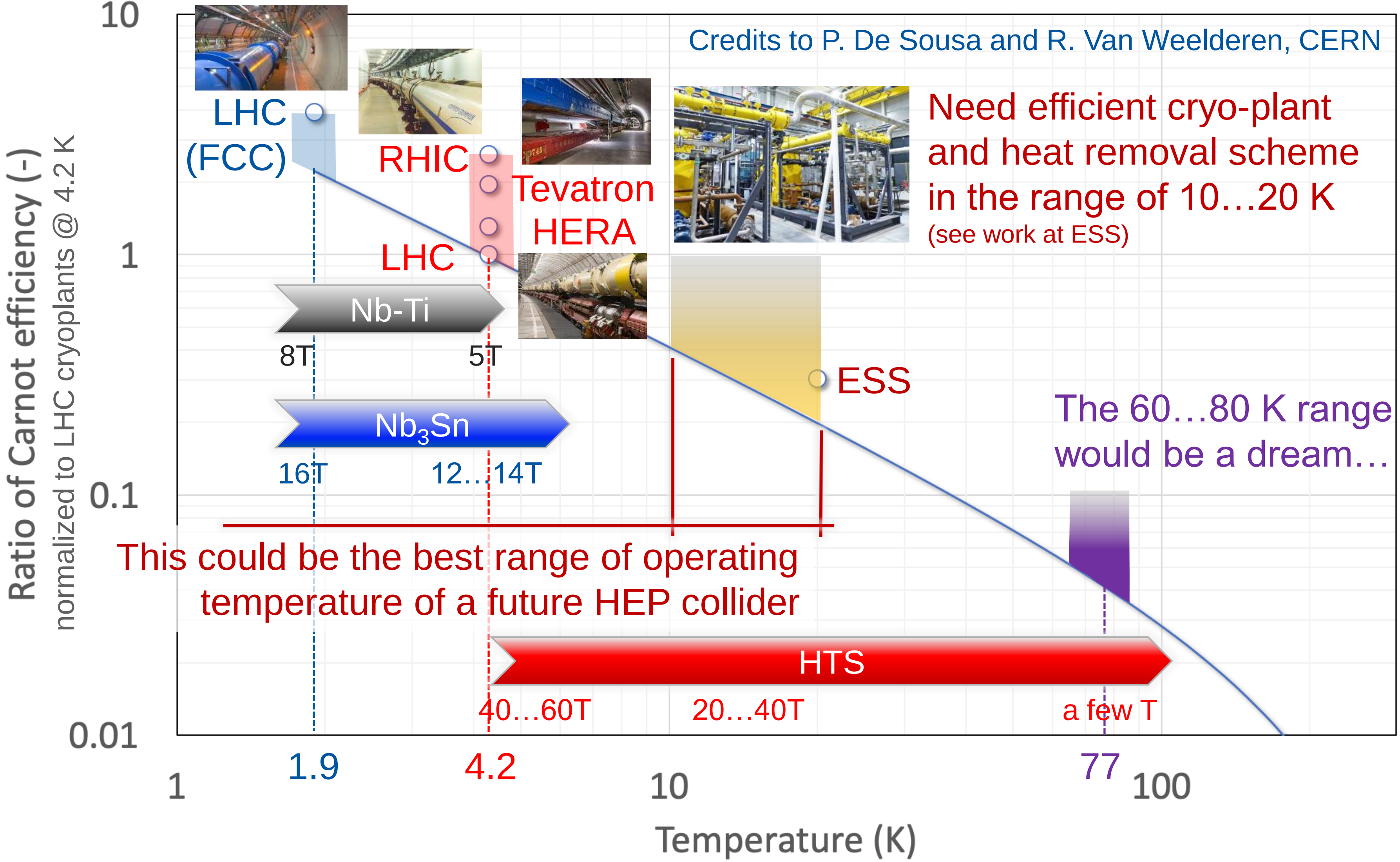
- Market shortage is affecting industrial and scientific customers
- Manufacturing industry contracts are impacted with volume limitations
- Large scientific instrument cannot do so & rely on established industrial partnership

Helium market still at risk in 2023 and for the coming years

- Uncertainty on the effective Russian production capacity and market access
- Algerian gas production transferred using pipeline instead of LNG
- No more back-up from the US federal authorities, Cliffside for sale ! (C&en News)

Courtesy of F. Ferrand, CERN

Energy efficient cryogenics



Credits to P. De Sousa and R. Van Weelderen, CERN

Need efficient cryo-plant and heat removal scheme in the range of 10…20 K

(see work at ESS)

The 60…80 K range would be a dream…

This could be the best range of operating temperature of a future HEP collider

Note(2): HTS offers efficiency and sustainability

Outline

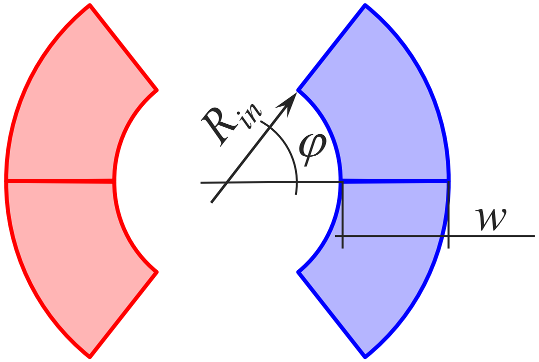
- HEP landscape
  - The need for high fields
  - The need for energy
  - The need for economics
- Case study: the Muon Collider
- HEP – For what ?
- Summary

The need for economics

- A large component in the magnet cost is the **amount of superconductor** (coil cross section)
- High-field superconductors are (significantly) more expensive than *good-old* Nb-Ti
- Need to work in two directions:
  - **Reduce the coil cross section (increase *J* !)**

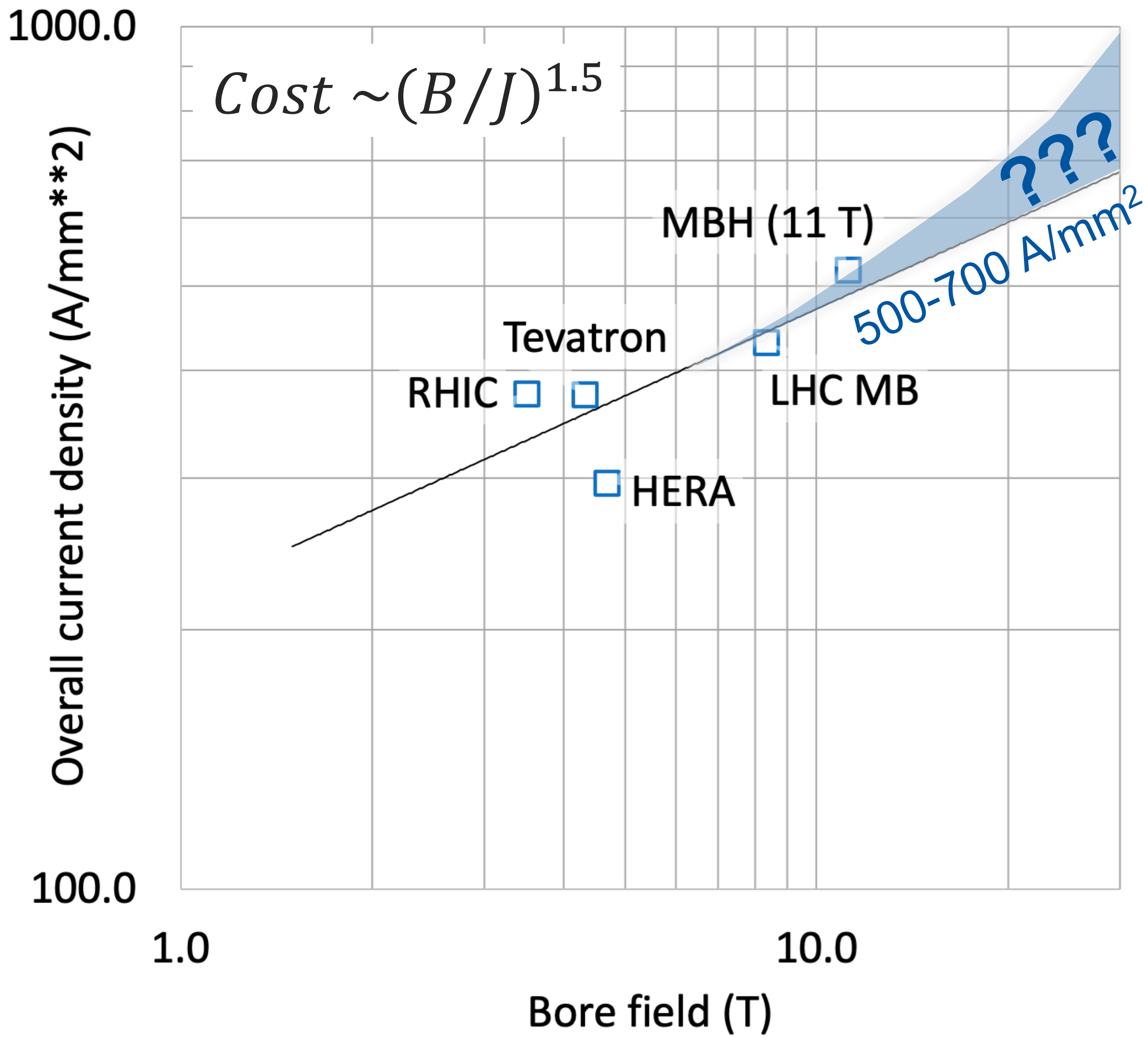
$$B = \frac{2\mu_0}{\pi} J w \sin(\varphi)$$

$$\boxed{A_{coil} = 2\varphi(w^2 + 2R_{in}w) \sim \frac{1}{J^{1.5}}}$$



  - **Reduce unit conductor cost**

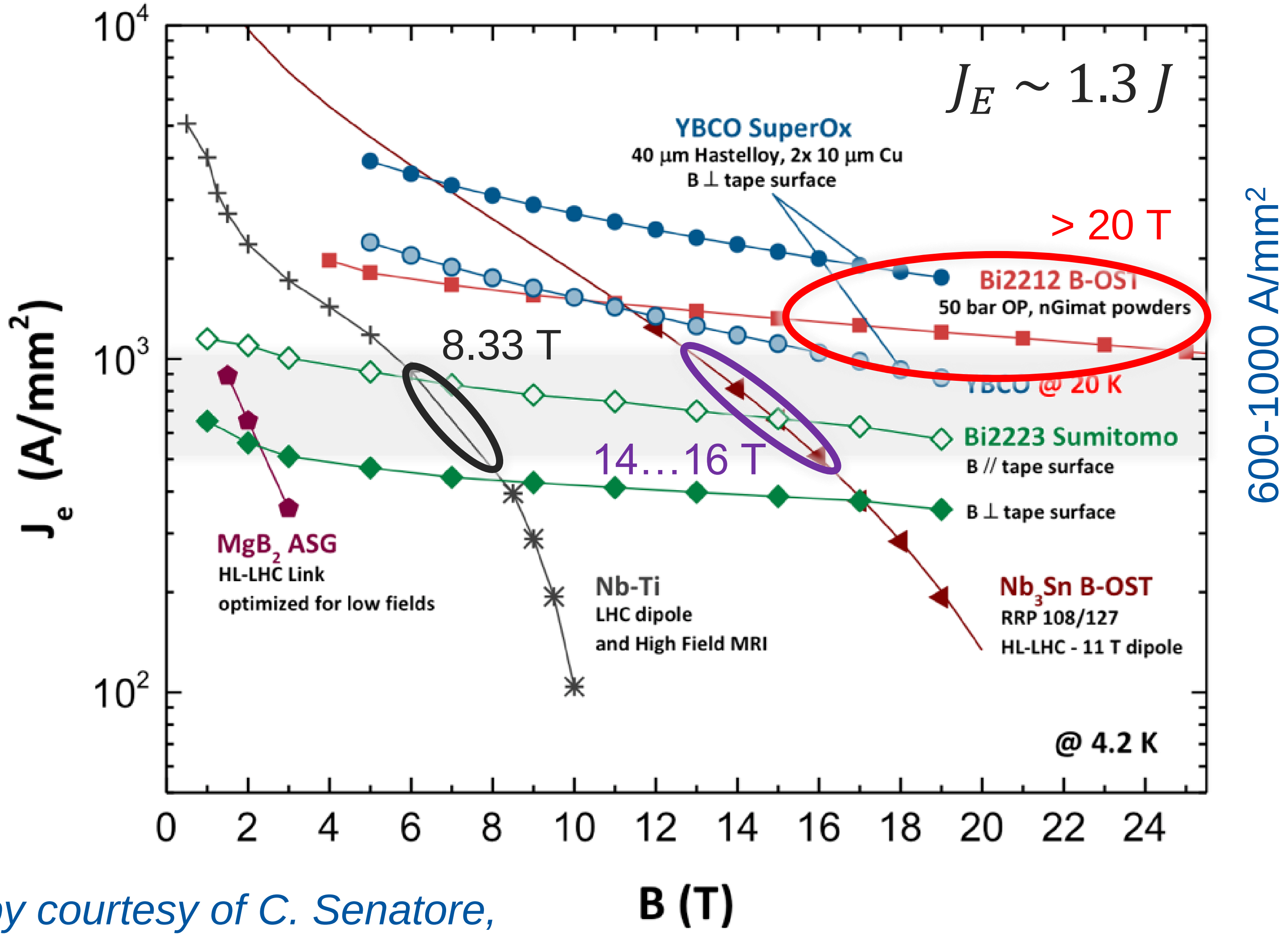
Engineering current density



The overall (coil) current density of the accelerator magnets of the past half century has increased steadily to **use at best the superconductor**, and thus **contain cost**

High field implies high current density

Critical engineering current density



Graphics by courtesy of C. Senatore, University of Geneva

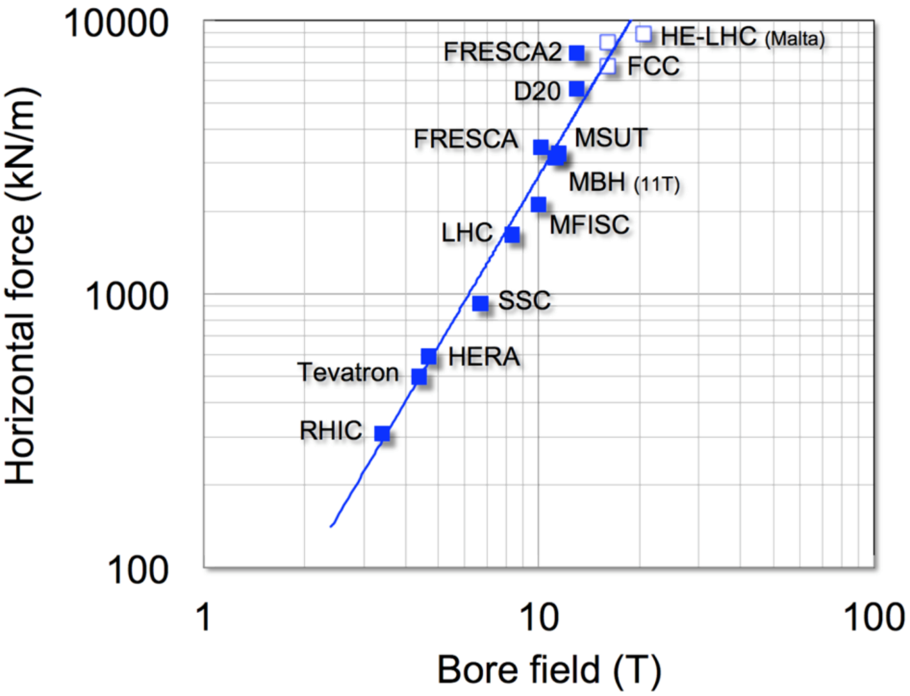
Note(3): HTS critical current density is not the limit

Limits of high fields

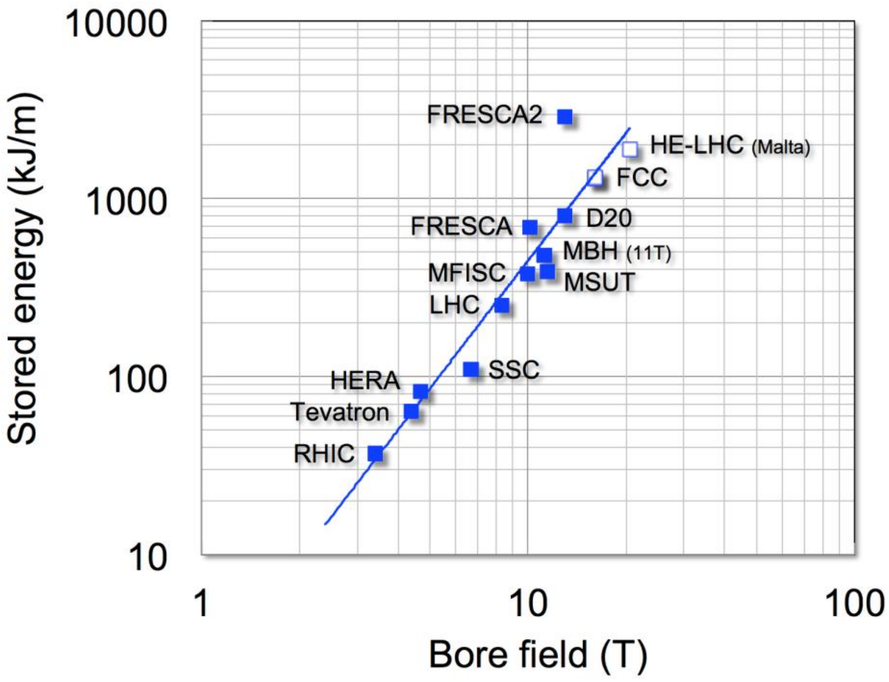
$$F_x = -F_y \approx \frac{4}{3}\frac{B^2}{2\mu_0}R_{in}$$

$$E/l = \frac{\pi B^2 R_{in}^2}{\mu_0}\left[1+\frac{2}{3}\frac{w}{R_{in}}+\frac{1}{6}\left(\frac{w}{R_{in}}\right)^2\right]$$

Lorentz forces on a quarter of a thin coil of radius R_{in} generating a dipole field B (thin shell approximation)



Energy per unit length in a sector coil of inner radius R_{in}, outer radius R_{out}, coil width w producing a dipole field B

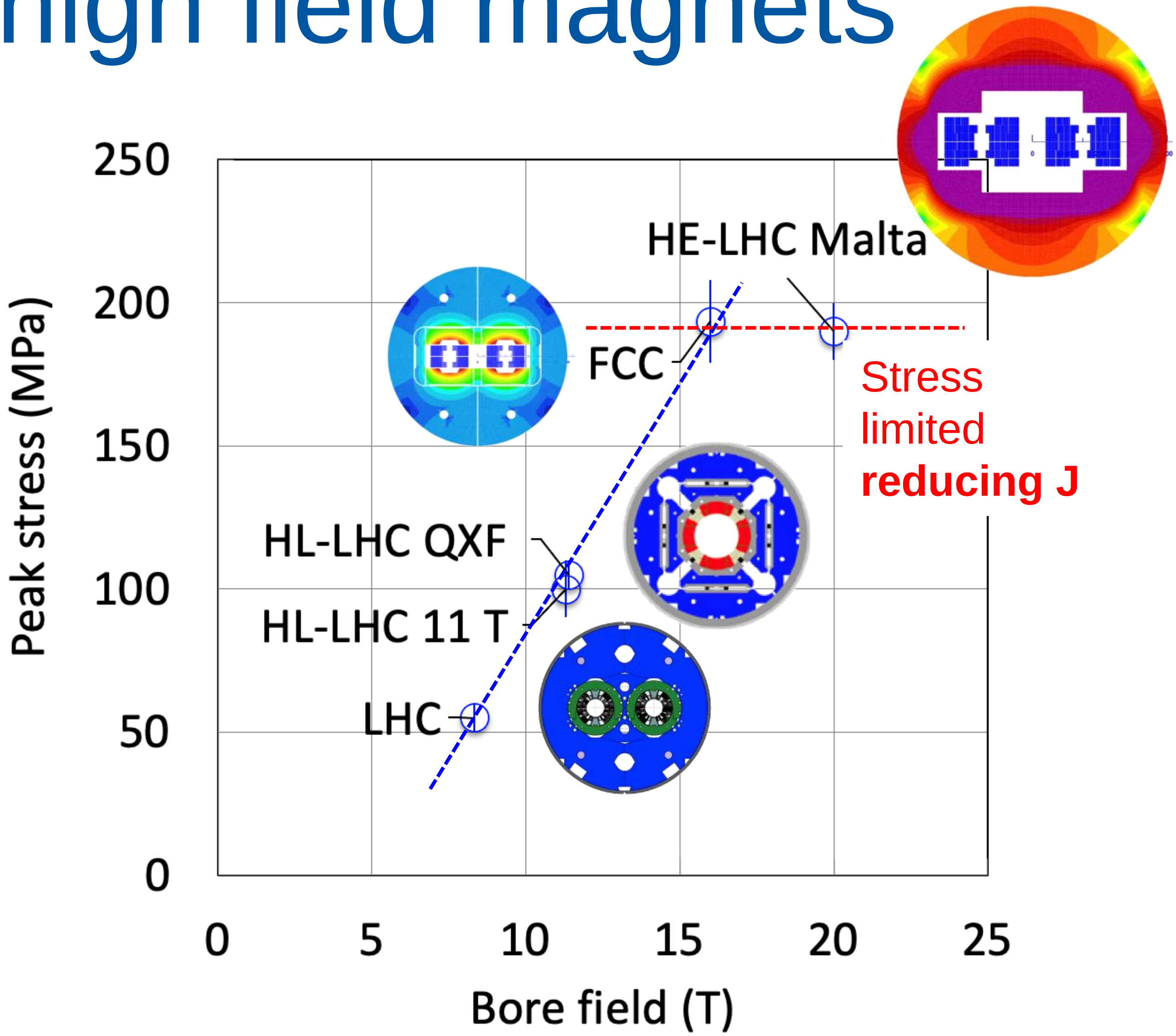


The limits are mechanics and quench management

Stress in high field magnets

$$F \mu B^2 \qquad w \mu \frac{B}{J}$$

$$s \gg \frac{F}{w} \mu JB$$

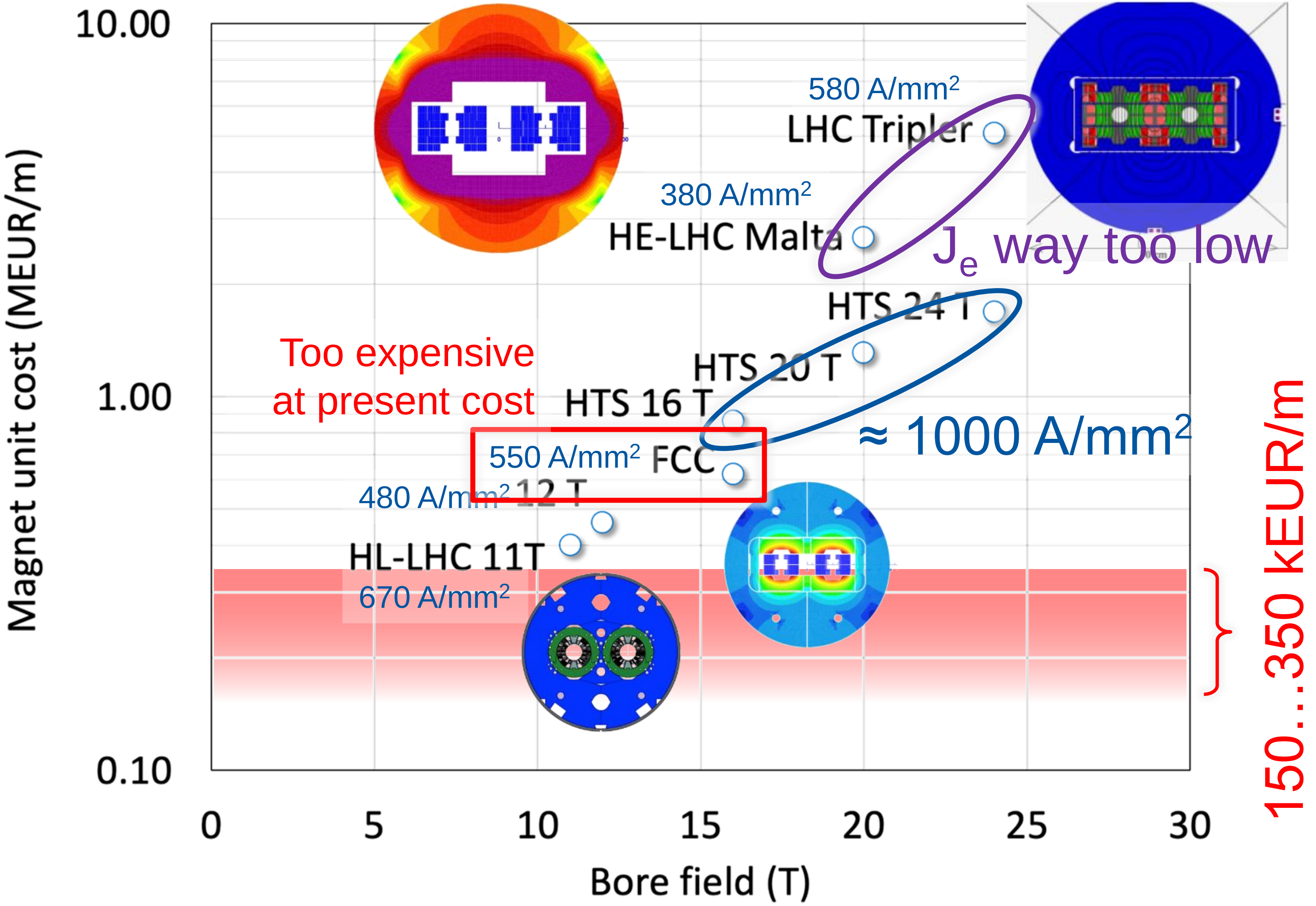


Stress limited **reducing J**

RECALL: *J* x *B* is also the scaling of the pinning force in a superconductor

Mechanics limits current density ?!?

Cost estimates (today)



Too expensive at present cost

J_e way too low

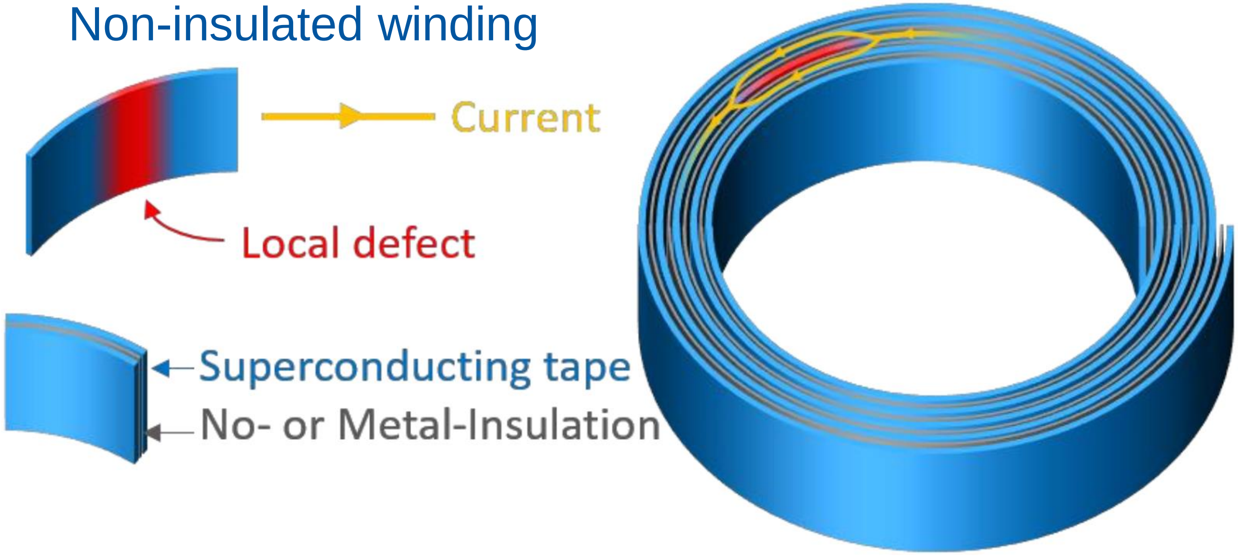
≈ 1000 A/mm²

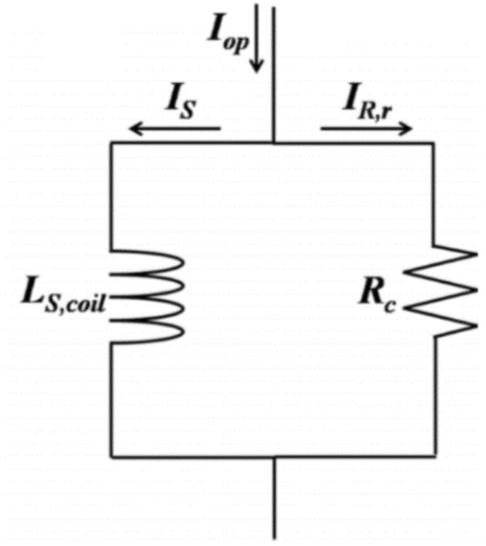
150…350 kEUR/m

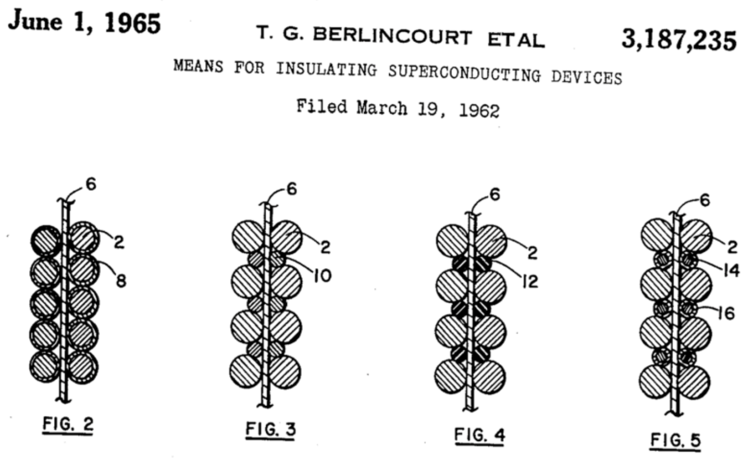
How to get to 1000 A/mm² ?

Back to the future – NI coils

Non-insulated winding





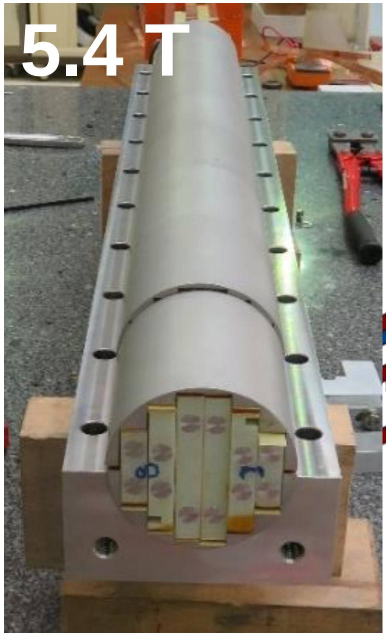

June 1, 1965 T. G. BERLINCOURT ETAL 3,187,235

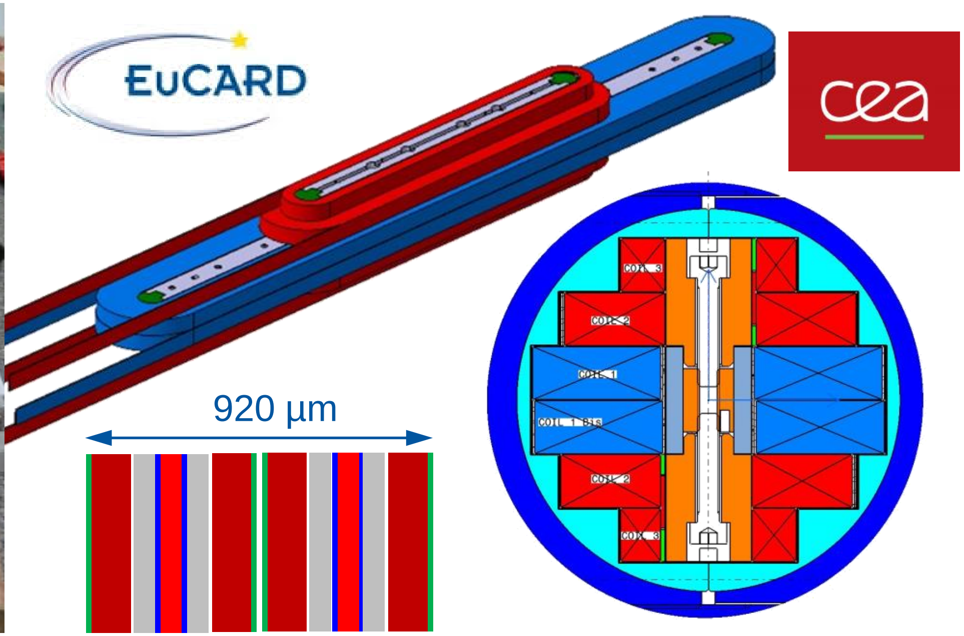
MEANS FOR INSULATING SUPERCONDUCTING DEVICES

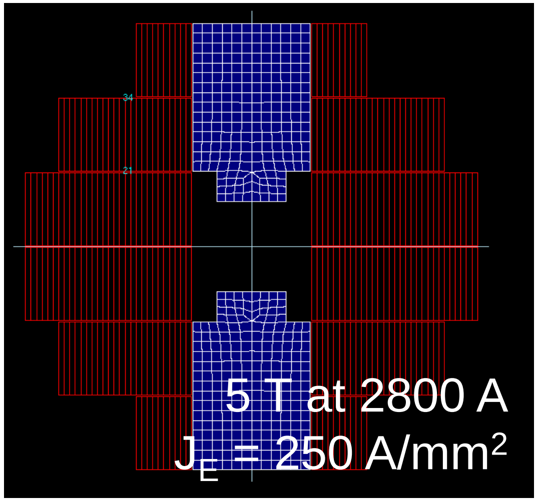
Filed March 19, 1962


Nb_3Sn tapes (12 mm width, 0.1 mm thickness) produced at RCA, 1965

HTS winding technology needed

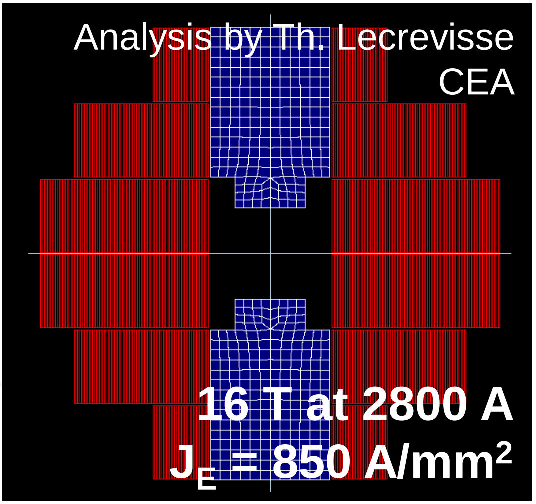






5 T at 2800 A

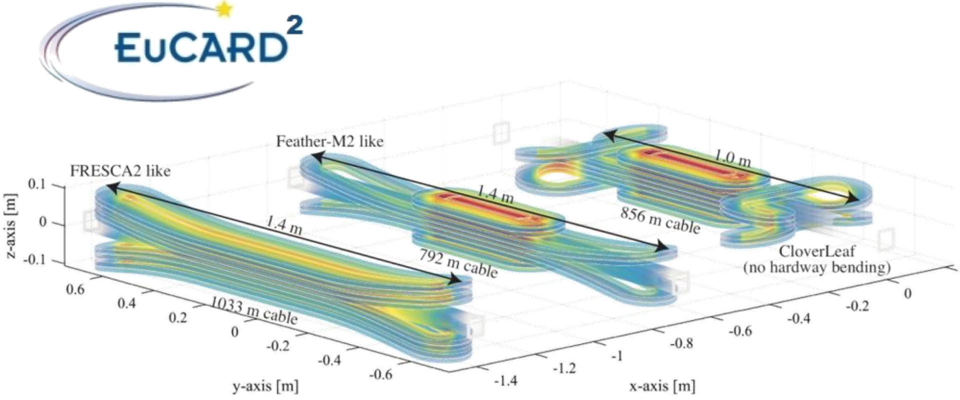
$J_E = 250$ A/mm^2



Analysis by Th. Lecrevisse
CEA

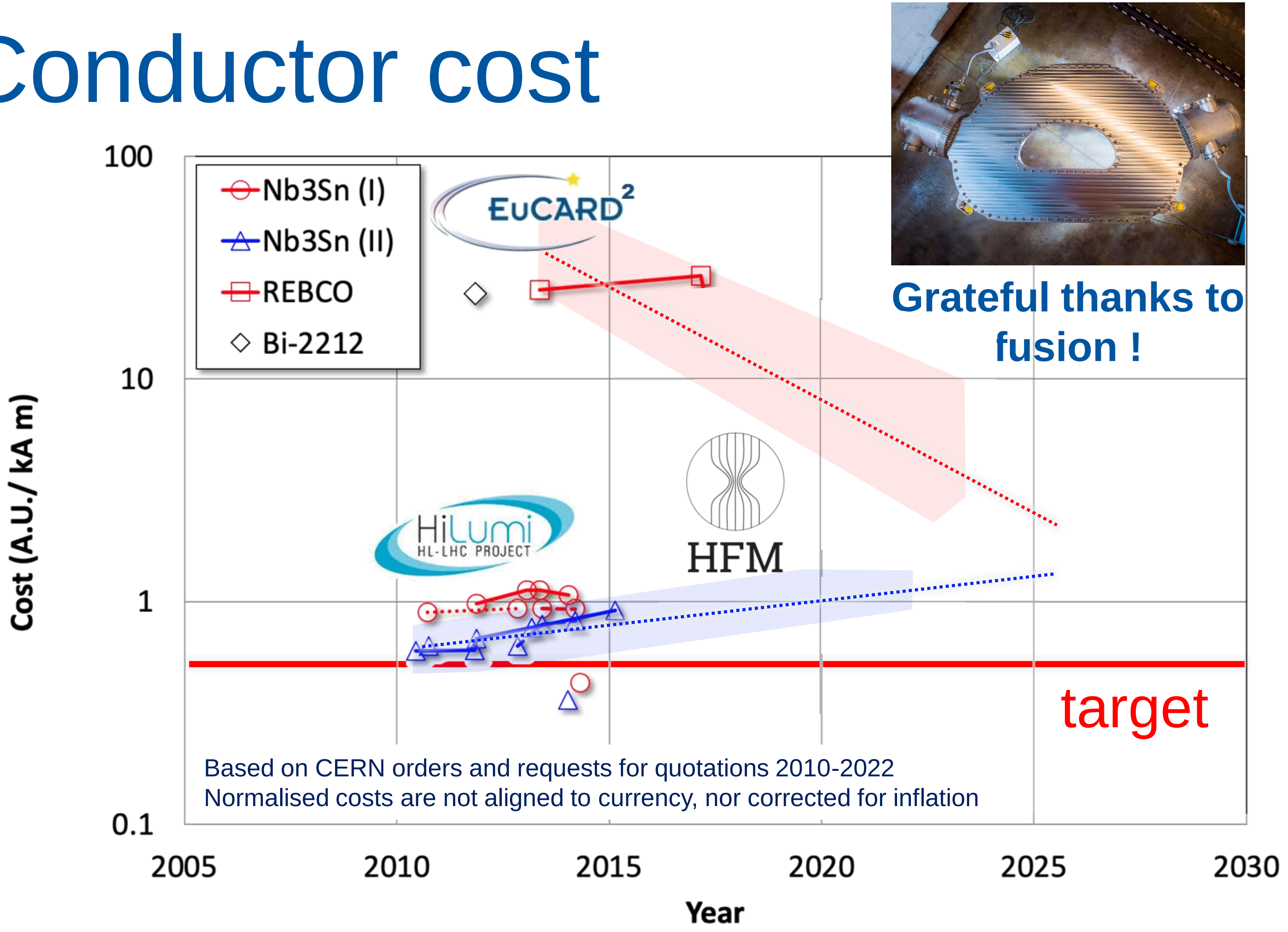
16 T at 2800 A

$J_E = 850$ A/mm^2



Note(4): HTS is ideally matched to NI technology

Conductor cost

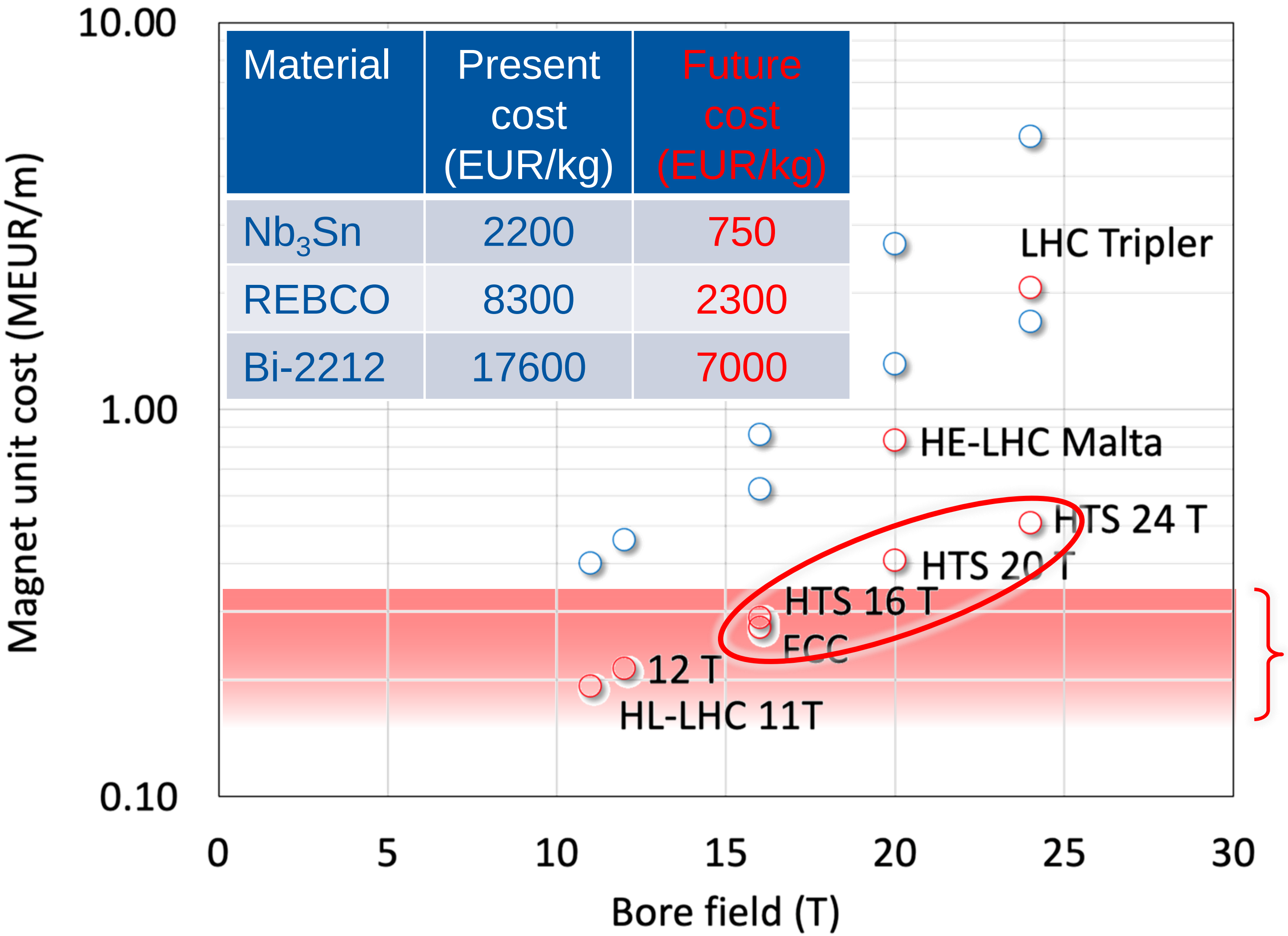


Based on CERN orders and requests for quotations 2010-2022
Normalised costs are not aligned to currency, nor corrected for inflation

Grateful thanks to fusion !

Note(5): HTS cost is decreasing fast !

Cost estimates (aspirational)



Material	Present cost (EUR/kg)	Future cost (EUR/kg)
Nb_3Sn	2200	750
REBCO	8300	2300
Bi-2212	17600	7000

150…350 kEUR/m

Note(6): HTS may be THE enabler for the next collider

Outline

- HEP landscape
  - The need for high fields
  - The need for energy
  - The need for economics
- Case study: the Muon Collider
- HEP – For what ?
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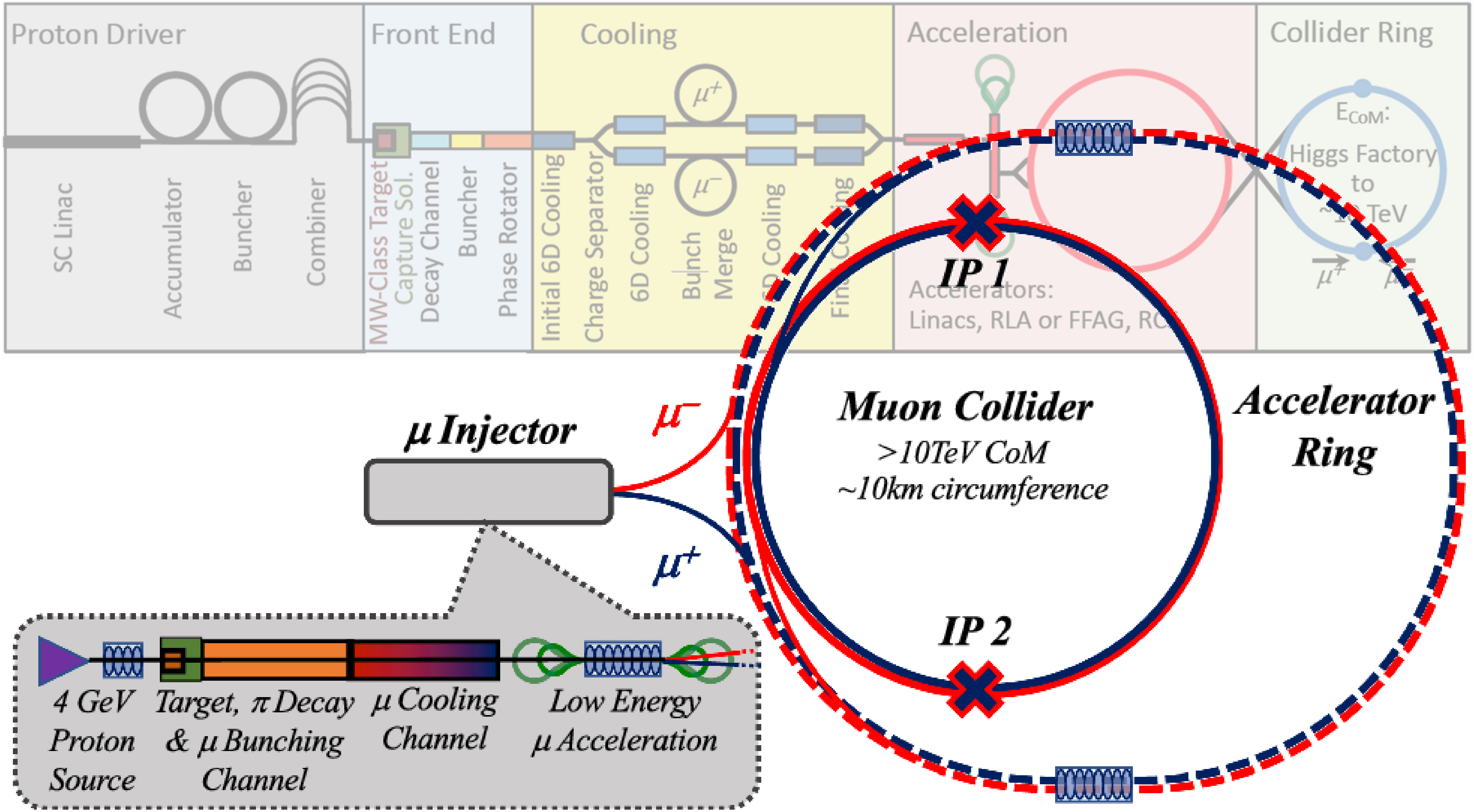
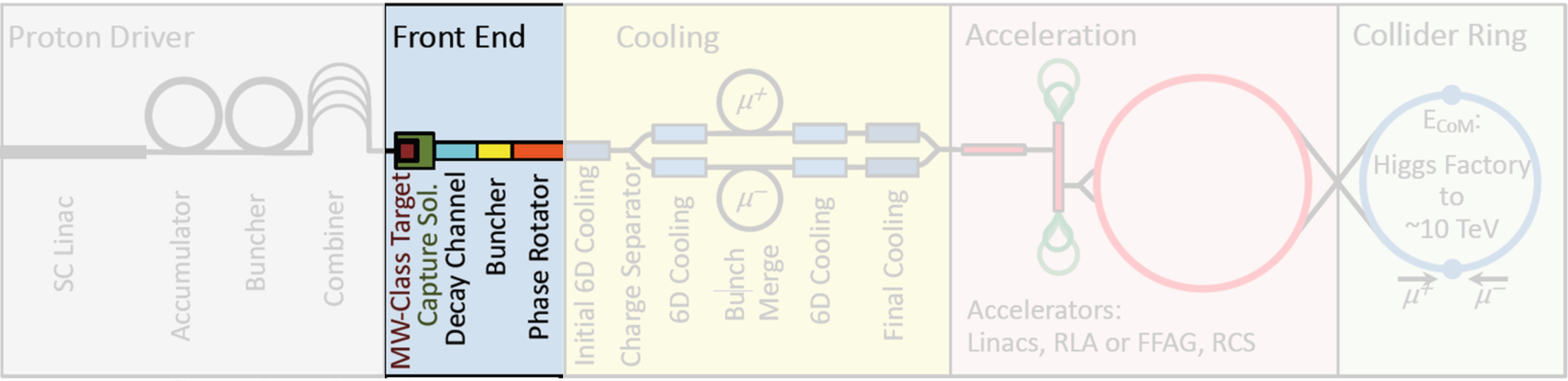
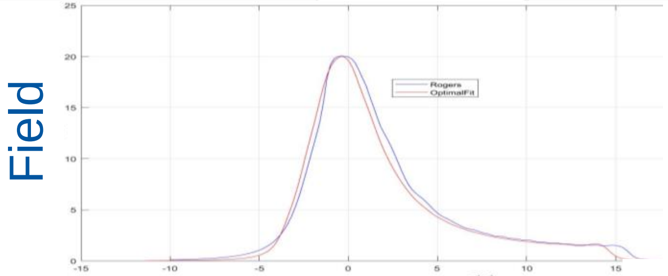
The Proton Driven Muon Collider



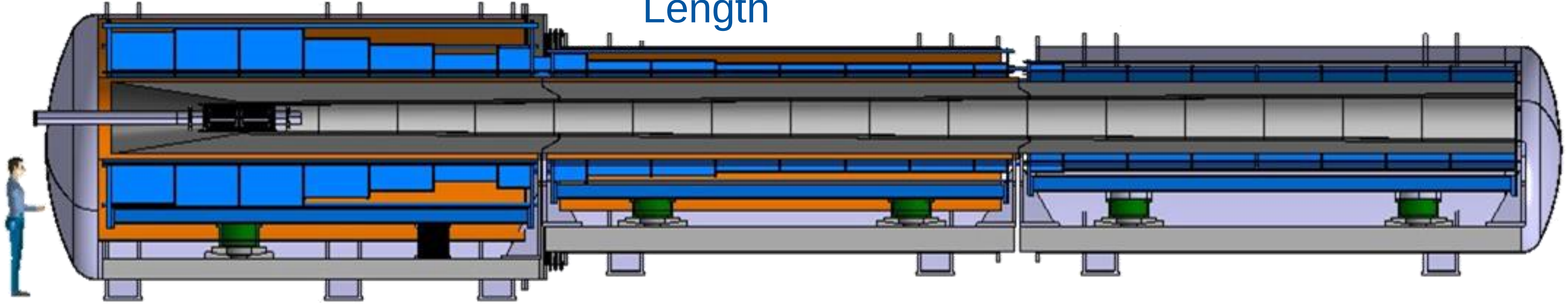
Target and capture solenoid



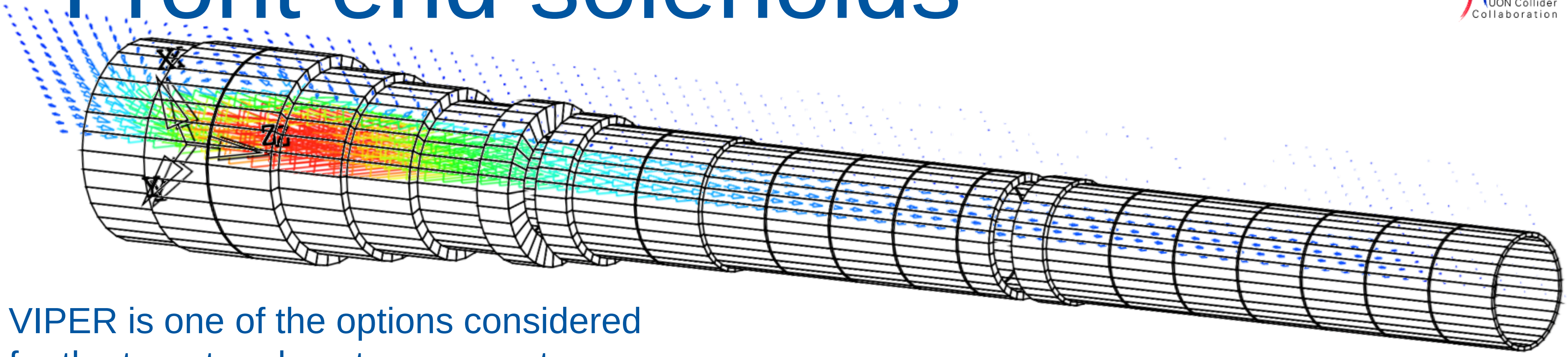


20 T, 200 mm (1/s^3 field decay)
Radiation heat load on coils ≈ 4 kW
Radiation dose ≈ 80 MGy

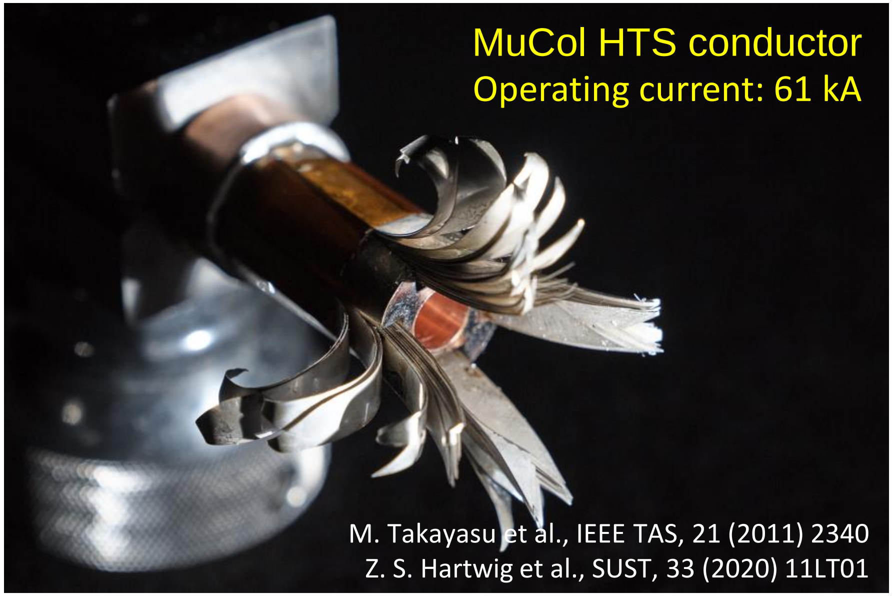
Length



Front end solenoids



VIPER is one of the options considered for the target and capture magnets, providing a “feasible” solution

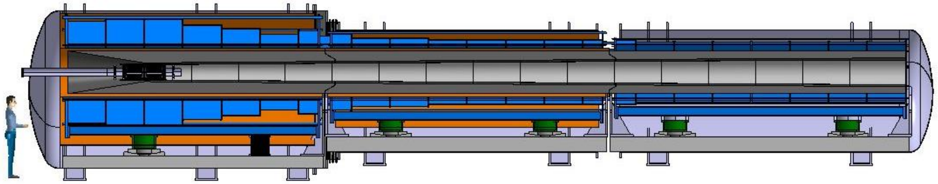


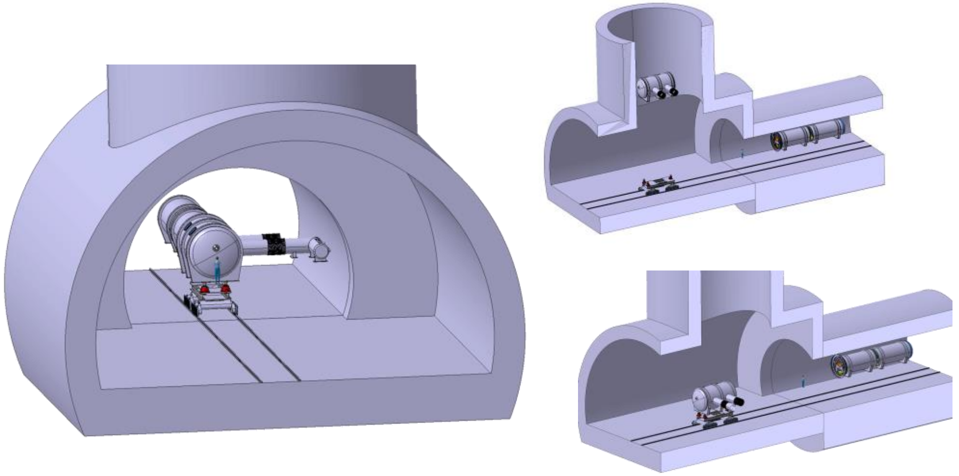
MuCol HTS conductor

Operating current: 61 kA

M. Takayasu et al., IEEE TAS, 21 (2011) 2340

Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

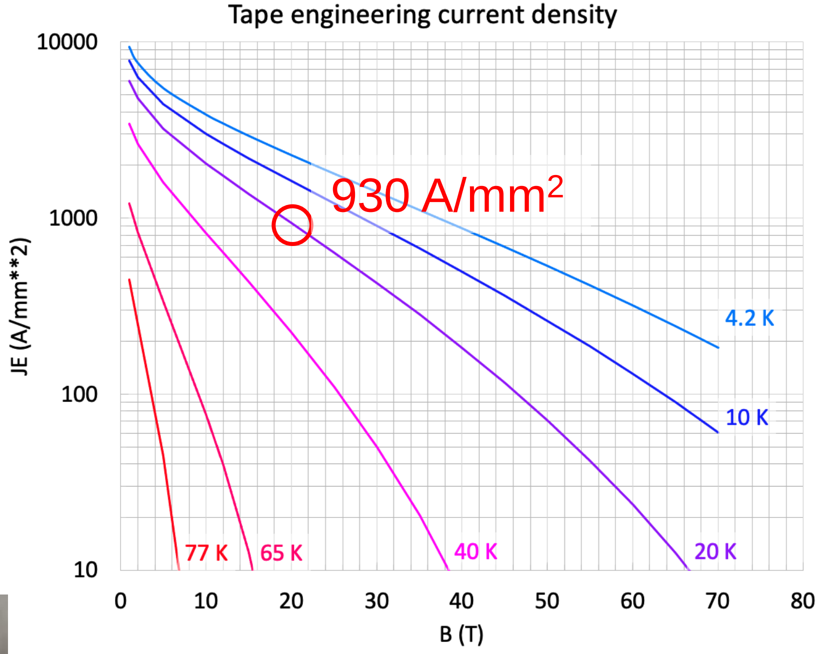




Courtesy of A Portone, P. Testoni, J. Lorenzo Gomez (F4E)
A. Kolehmainen, C. Accettura (CERN)

Conductor design

HTS tape thickness	(μm)	62
HTS tapes	(-)	80
HTS stack width	(mm)	6
HTS stack thickness	(mm)	5
HTS stack width	(mm)	6
Number of HTS stacks	(-)	4
Copper diameter	(mm)	23
Hole diameter	(mm)	8
Wetted perimeter	(mm)	25
Wrap thickness	(mm)	0.25
Jacket outer dimension	(mm)	39.5



$$J_C = \frac{C_0}{B} h(t) f_p(b)$$

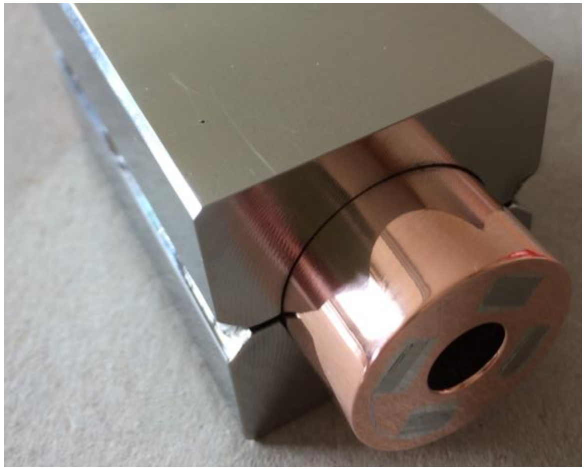
$$B_{irr}(T) = B_{irr0}\left(1 - \frac{T}{T_{irr0}}\right)^{\nu}$$

$$T_{irr}(B) = T_{irr0}\left(1 - \frac{B}{B_{irr0}}\right)^{\frac{1}{\nu}}$$

$$h(t) = (1 - t^{\nu})(1 - t^{m})$$

$$f_p(b) = b^p (1 - b)^q$$

$$t = \frac{T}{T_{irr0}} \qquad b = \frac{B}{B_{irr}(T)}$$



I_{op} = 61 kA

B_{op} = 20 T

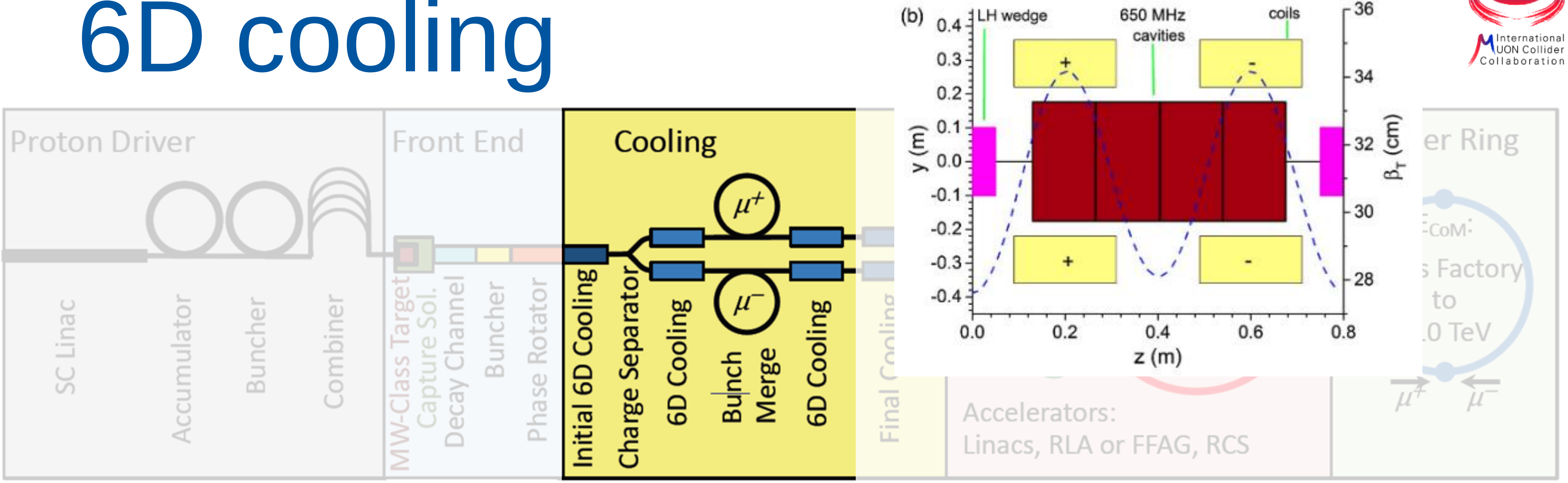
T_{op} = 20 K

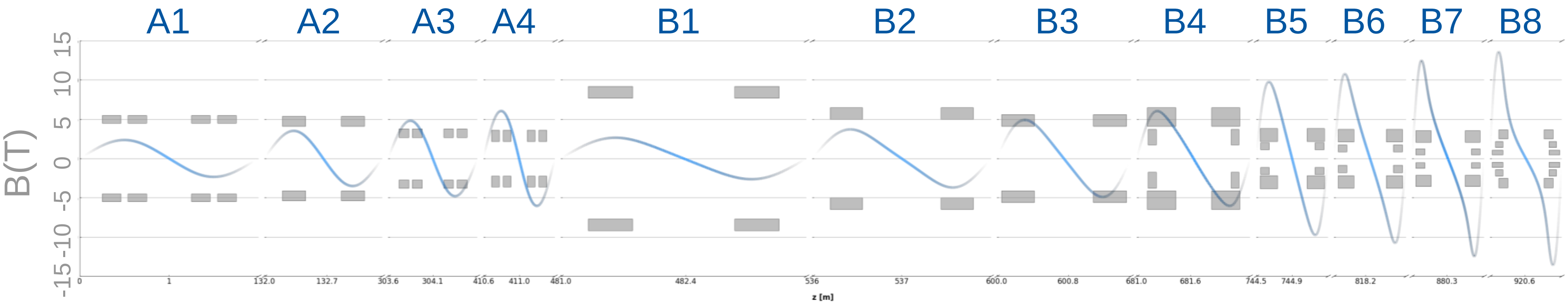
T_{cs} = 29.7 K

Temperature margin ΔT **is about 10 K** at nominal conditions of current, field and temperature

Stability is not an issue for HTS

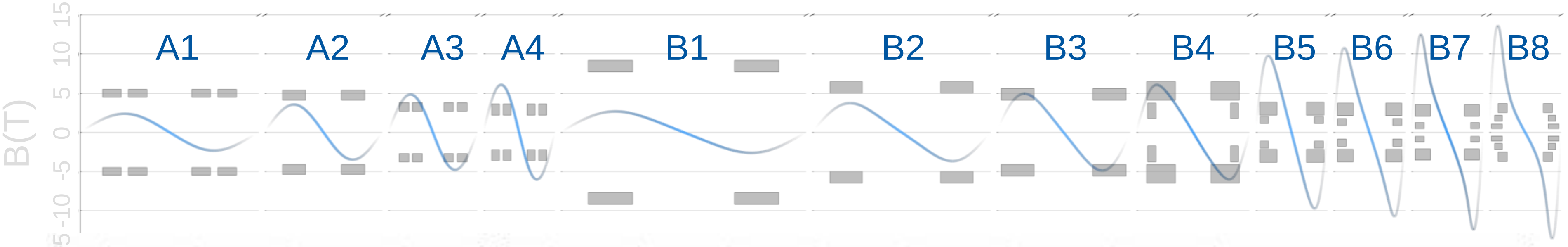
6D cooling





2.4 T to 13.6 T on axis
Bore size from 90 mm to 1.5 m

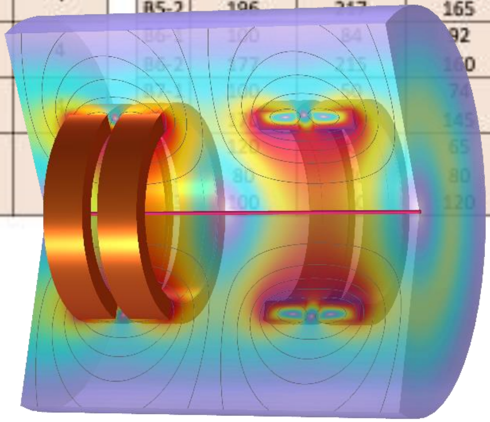
6D Cooling solenoids



Stage	Cell length	Peak axis B	Stored energy	Coils/cell
	(m)	(T)	(MJ)	(-)
A1	2	2.4	5.4	4
A2	1.32	3.5	15.4	2
A3	1	4.8	7.2	4
A4	0.8	6.1	8.4	4
B1	2.75	2.6	44.5	2
B2	2	3.7	24.1	2
B3	1.5	4.9	29.8	2
B4	1.27	6	24.4	4
B5	0.806	9.8	12	4
B6	0.806	10.8	8.2	4
B7	0.806	12.5	5.7	[illegible]
B8	0.806	13.6	1.4	[illegible]

Coil	Length	Radius	Thickness	Current density	Peak coil B	Hoop stress	Radial stress	Technology		
	(mm)	(mm)	(mm)	(A/mm^2)	(T)	(MPa)	(MPa)	Nb-Ti 4K	Nb$_3$Sn 4K	HTS 4K/20K
A1-1	210	450	100	63.25	4.1	34	-4.6	✓	✓	✓
A2-1	260	410	130	126.6	9.5	137	-28.3		✓	✓
A3-1	110	270	110	165	9.4	138	-28.5		✓	✓
A4-1	90	220	140	195	11.6	196	-49.4		✓	✓
B1-1	500	770	150	69.8	6.9	95	-13.5	✓	✓	✓
B2-1	360	500	150	90	8.4	114	-20.1		✓	✓
B3-1	370	410	150	123	11.2	174	-36.6		✓	✓
B4-1	92	175	200	94	9.2	231	-0.1/19.7		✓	✓
B4-2	320	410	240	70.3	7.8	66	-23.5		✓	✓
B5-1	100	113	88	157	13.9	336	-0.7/21.1		...	✓
B5-2	196	217	165	168	12.3	159	-55.7		✓	✓
B6-1	100	84	92	185	14.2	314	-1.4/22.3		...	✓
B6-2	177	215	160	155.1	10.3	118	-43.1		✓	✓
B7-1	100	[illegible]	74	198	14.3	244	-1.1/20.7		...	✓
[illegible]	[illegible]	[illegible]	145	155	10.1	119	-37.4		✓	✓
[illegible]	120	[illegible]	65	220	15.1	119	-3.0/22.1		...	✓
[illegible]	80	[illegible]	80	135	6.2	110	-2.4/4.5	✓	✓	✓
[illegible]	100	[illegible]	120	153	6.2	41	-22.9	✓	✓	✓

Coil size



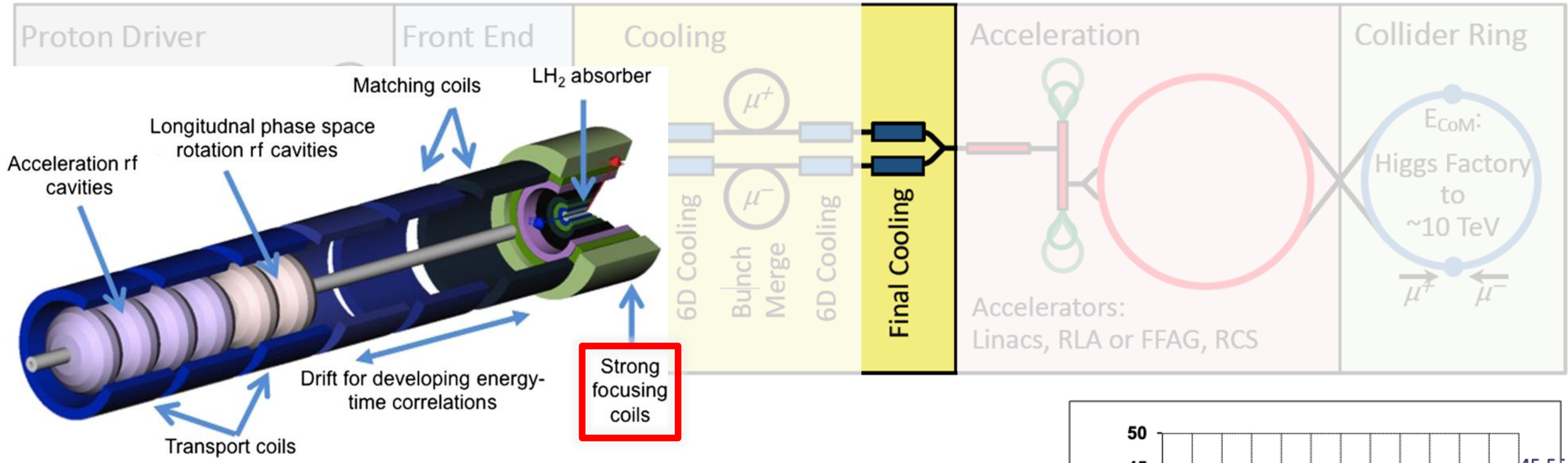
Quench protection

Margin

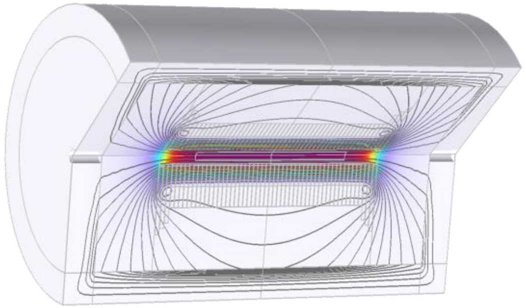
Mechanics

Courtesy of J. Pavan, UMIL, and S. Fabbri, CERN

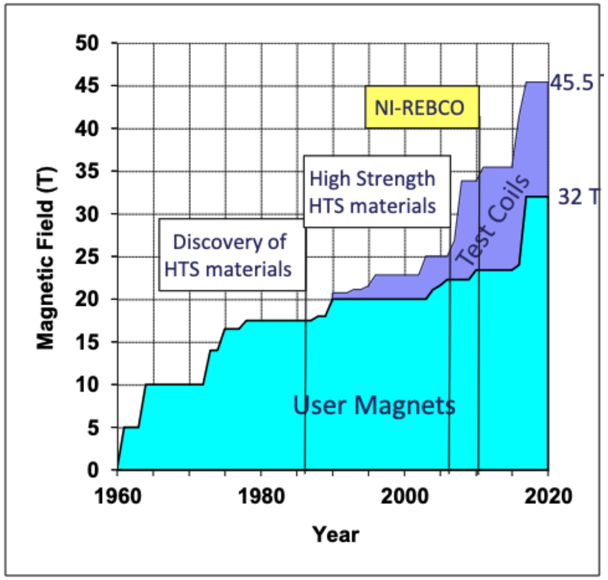
Final cooling



> 40 T on axis
Bore size 50 mm

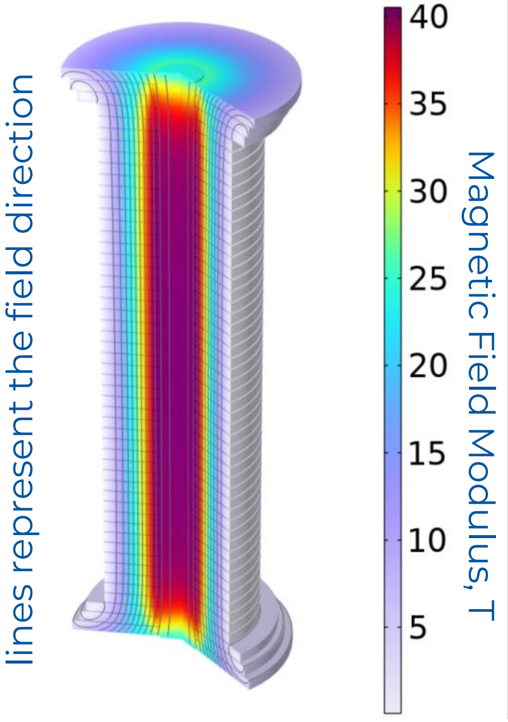


Highest field reached in solenoids using insulated HTS (32 T REBCO insert in LTS outsert) and non-insulated HTS (45.5 T REBCO insert in resistive outsert)



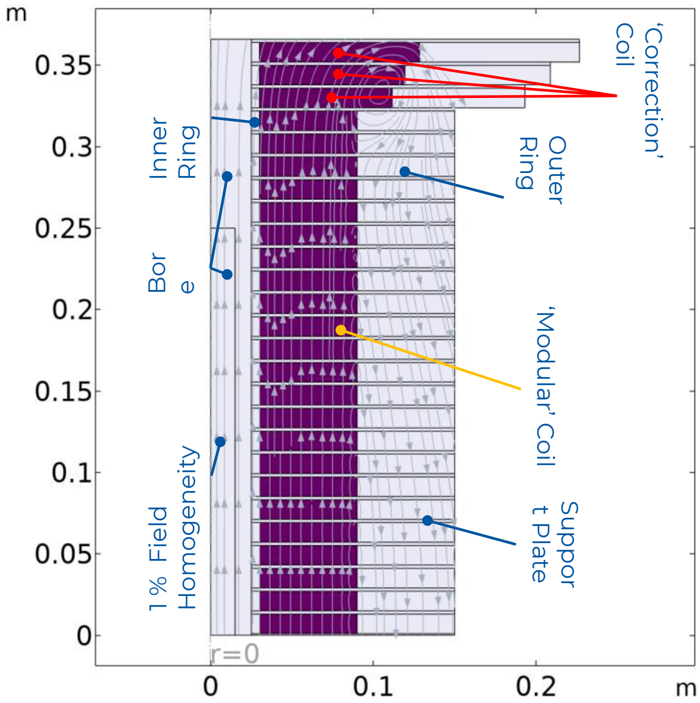
Final cooling (40 T) concept

$$B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0} \xrightarrow{\sigma_{max} = 600\ \text{MPa}} B_{max} \approx 55\ \text{T}$$



- **Modular** pancake design with supporting *ring and plates* to manage hoop, radial and vertical stresses
- Free bore **50 mm**
- Inner ring thickness 5 mm
- Coil **winding thickness 60 mm**
  - **J_e = 632 A mm^{-2} → 40 T**
- Outer ring thickness *60 mm*
  - **Outer radius 150 mm**
- Horizontal plate thickness 2 mm

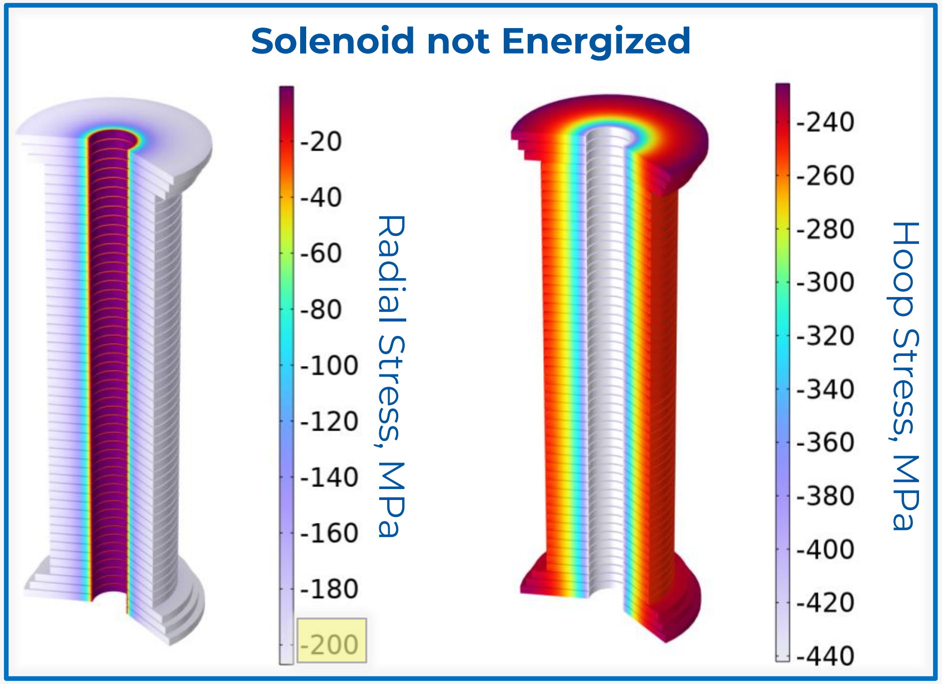
Cross Section of ¼ Solenoid

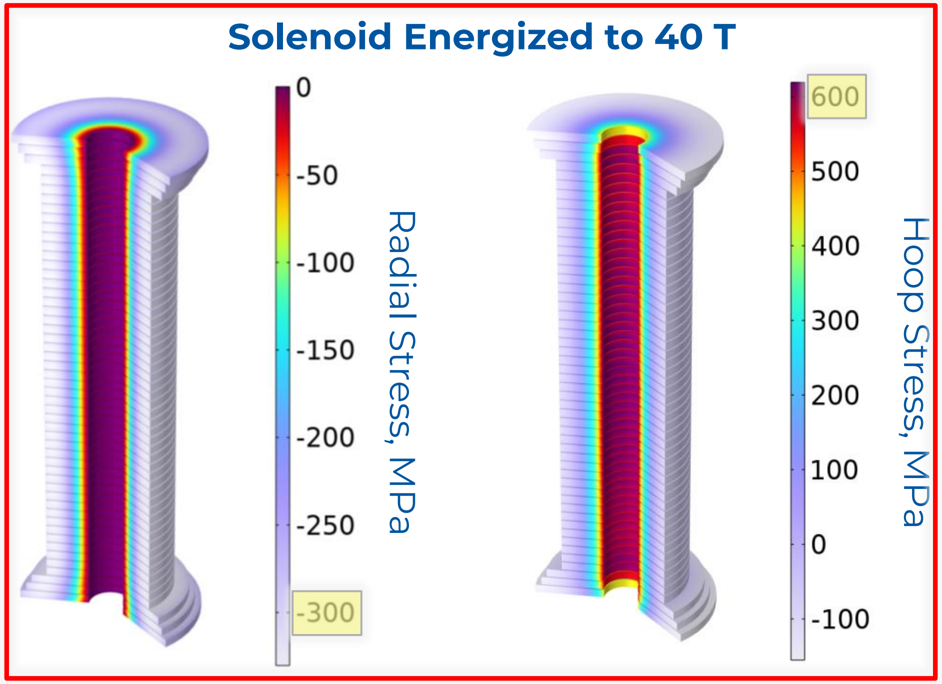


46 identical **'modular'** pancakes and **6 'correction'** pancakes are used to straighten the field lines at the solenoid ends

Courtesy of B. Bordini and A. Dudarev, CERN

Final cooling (40 T) mechanics


Solenoid not Energized

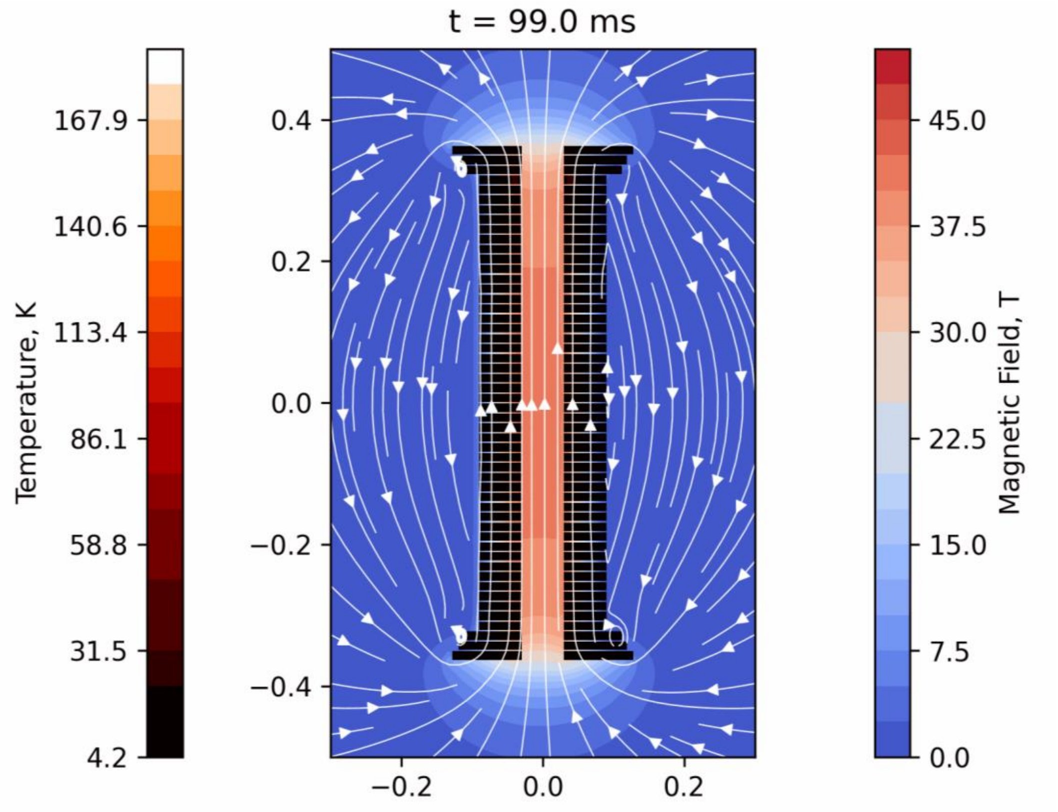

Solenoid Energized to 40 T

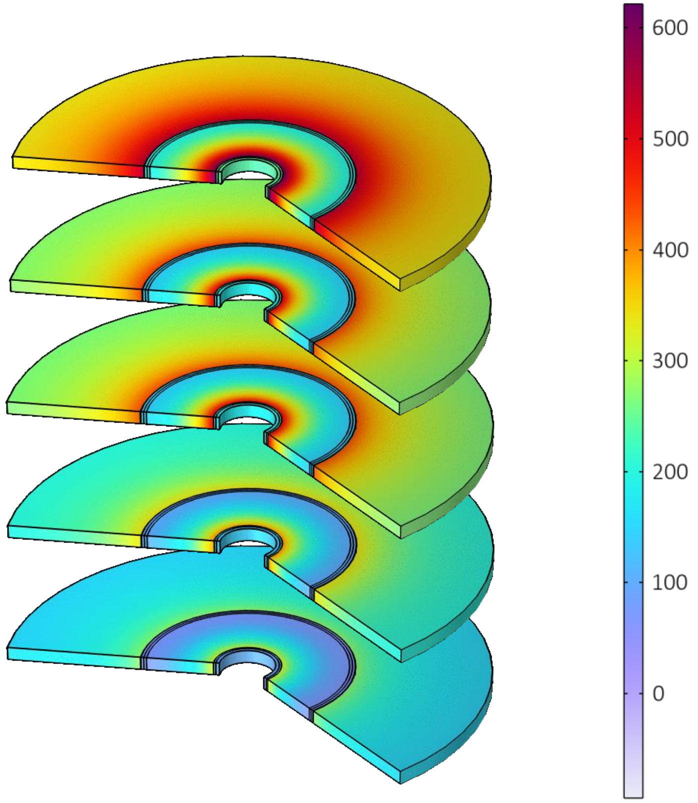
Preloading, a **radial precompression of ~ 200 MPa** is essential to limit the conductor hoop stress to acceptable values and to prevent tensile radial stress.

Electro-mechanical design and tests are in progress to validate the concept and identify issues/solutions towards assessing the performance limits.

Courtesy of B. Bordini and C. Accettura, CERN

Final cooling (40 T) quench

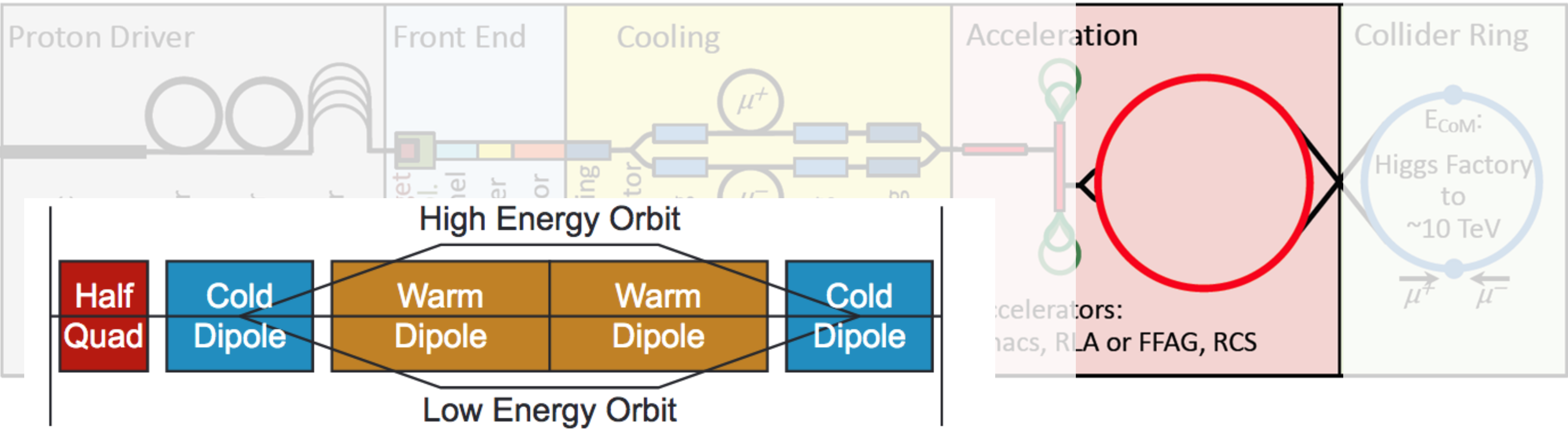




At this magnet scale (i.e. stored energy and size) a **non-insulated winding** seems to be a good option for quench management. Transverse resistance control in a range suitable for operation, balancing protection, mechanics, ramp time and field stability will be crucial (**priority R&D**)

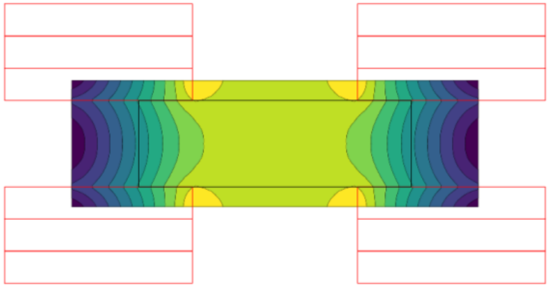
Courtesy of T. Mulder and G. Vernassa, CERN

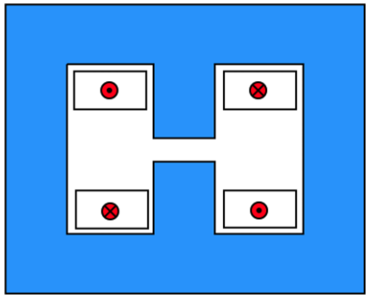
Acceleration (RCS & HCS)



10 T steady state
30x100 mm aperture

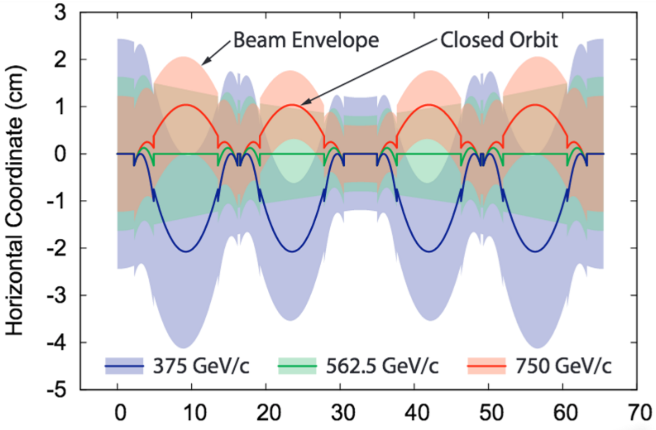
+/- 1.8 T up to 4 kT/s
30 x 100 mm aperture





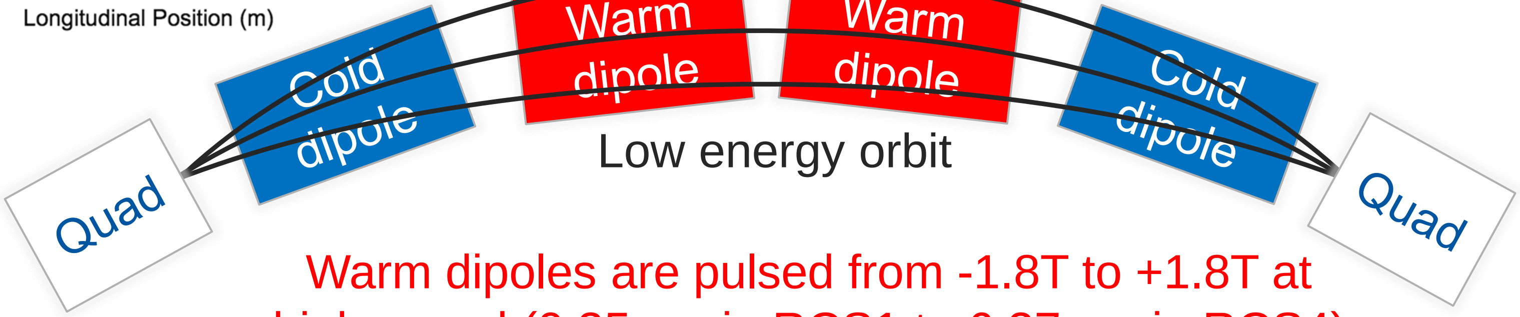
Acceleration (HCS)

The closed orbit swings by a few mm during a ramp



Hybrid Cycled Synchrotron

Cold dipoles provide a steady baseline field of about 10 T that offsets the integrated field. This makes the machine shorter, compared to a resistive machine pulsing from 0 to 1.8 T

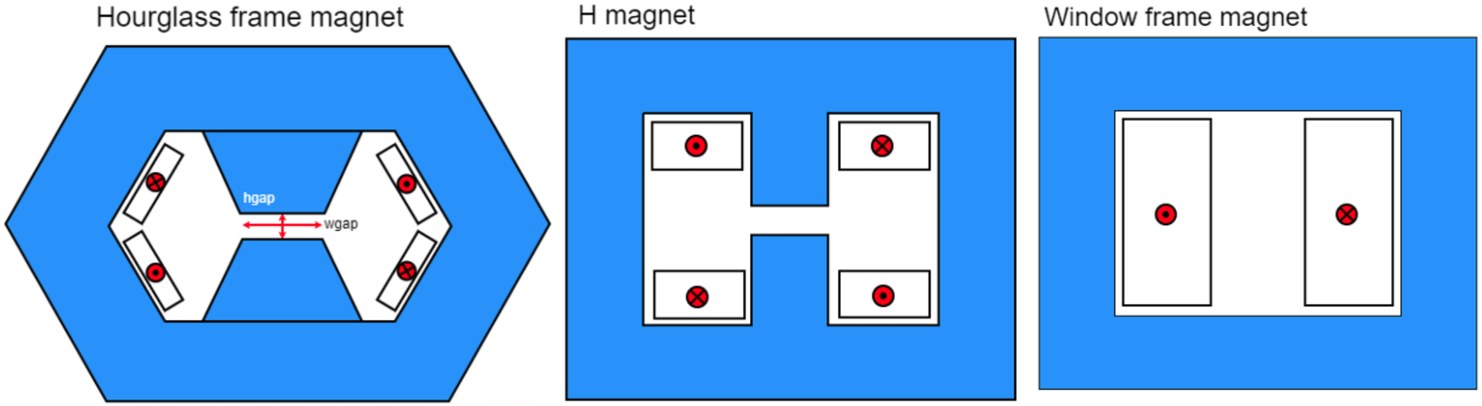


Warm dipoles are pulsed from -1.8T to +1.8T at high speed (0.35 ms in RCS1 to 6.37 ms in RCS4) every 200 ms. This allows to generate a 3.6 T field swing, but requires ramp-rates up to 4 kT/s

Fast pulsed magnets

$$E_{gap} = w\,h\,\frac{B^2}{2\mu_0}$$

$$E_{gap} \approx 3.9\ \mathrm{kJ/m}$$



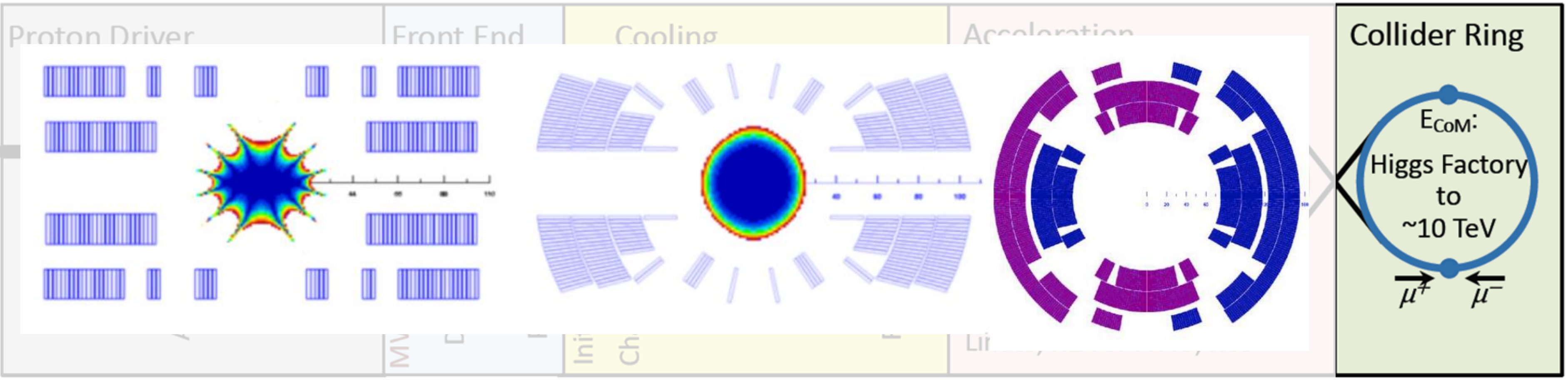
5.07 kJ/m | 5.65…7.14 kJ/m | 5.89 kJ/m

- A simple calculation
  - L_{mag}=10 km ⇒ E_{mag}=50 MJ ⇒ P_{mag}=50 GVA
- The main challenge is the management of the power in the resistive dipoles (several tens of GVA)
  - Minimum stored magnetic energy
  - Highly efficient energy storage and recovery

Courtesy of M. Breschi, P.L. Ribani, R. Miceli, UniBO

Collider

Designs from US-MAP



Arc:

- Combined function magnets: B1, B1+B2 and B1+B3
- B ≈ 8…16 T; G ≈ 320 T/m; G’ ≈ 7100 T/m^2
- Aperture ≈ 160 mm

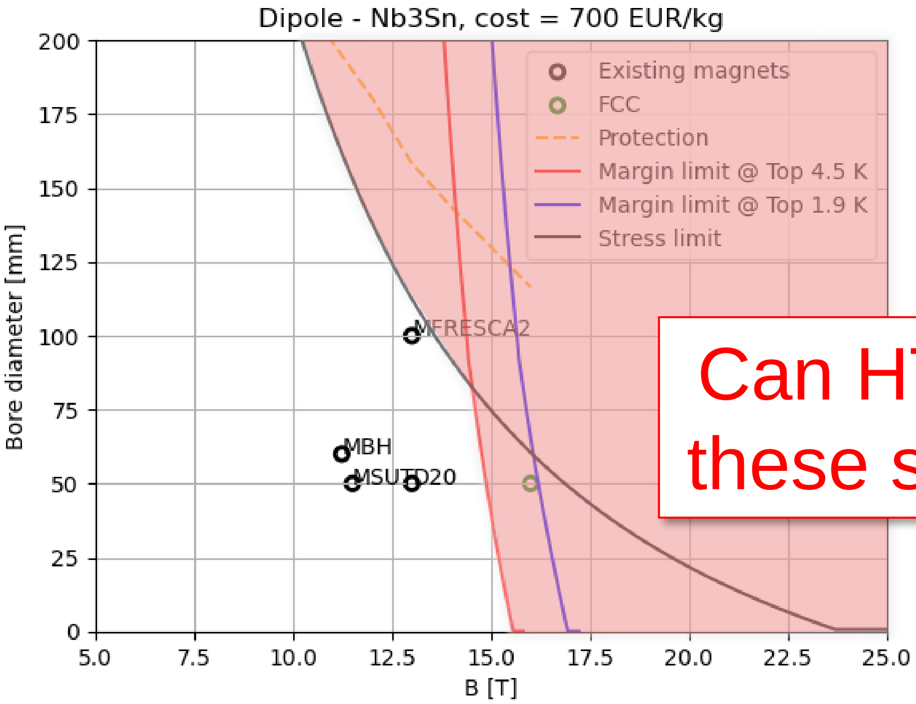
Final focus

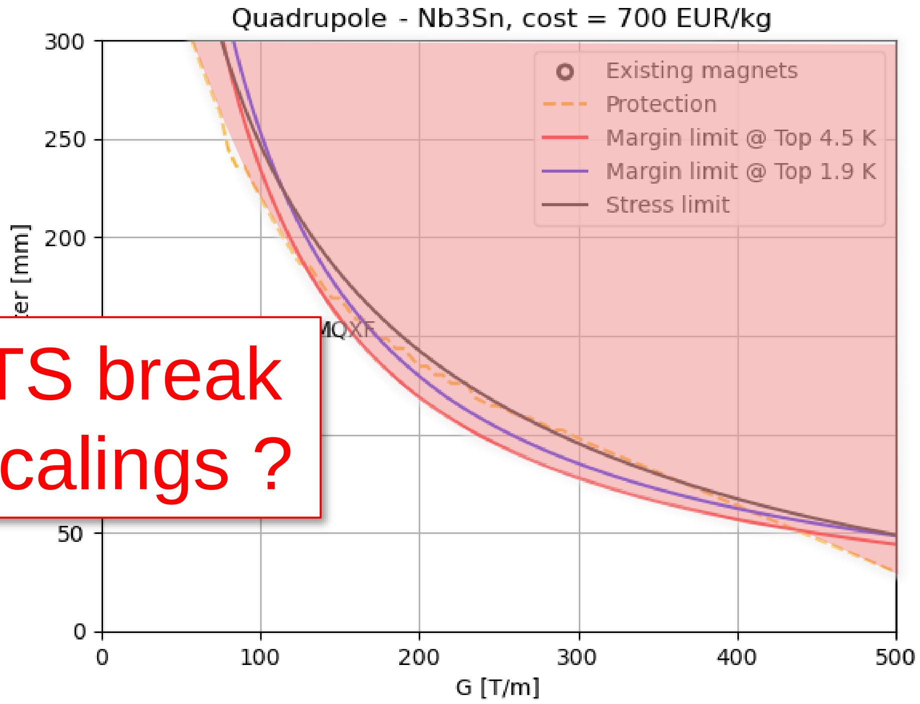
- Combined function magnets: B1, B2, B1+B2, B1+B3
- B ≈ 4…16 T; G ≈ 100…300 T/m; G’ ≈ 12000 T/m^2
- Aperture ≈ 120…300 mm

Difficult to define a single magnet spec

A-B plots

- Apply parametrically the design methods you learnt for (i) margin, (ii) peak stress, (iii) quench protection and (iv) limit total cost
- Find the performance limits in terms of maximum magnet aperture (A) vs. bore field (B)





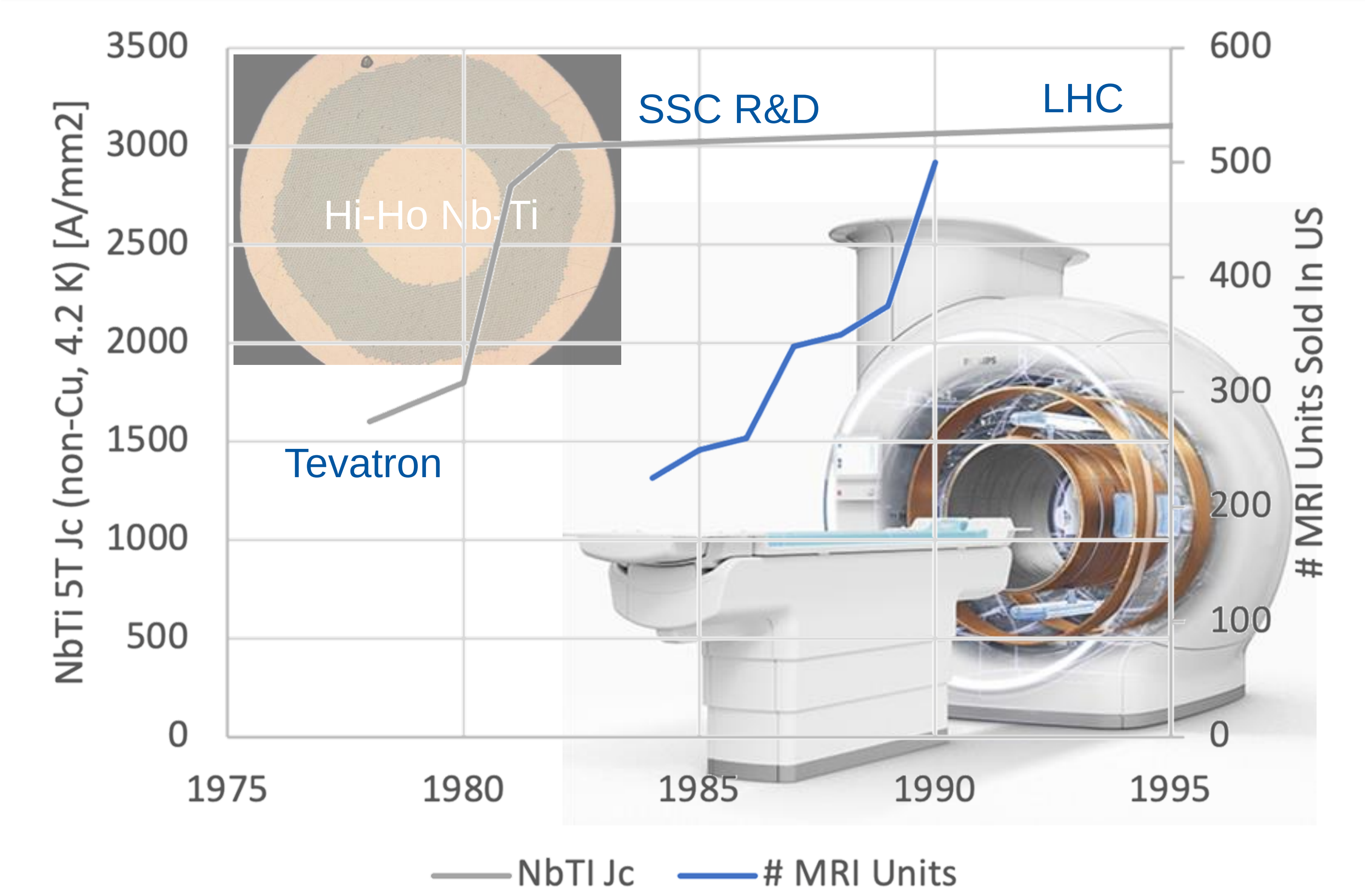
Can HTS break these scalings ?

Courtesy of D. Novelli (INFN) and T. Salmi (TUT)

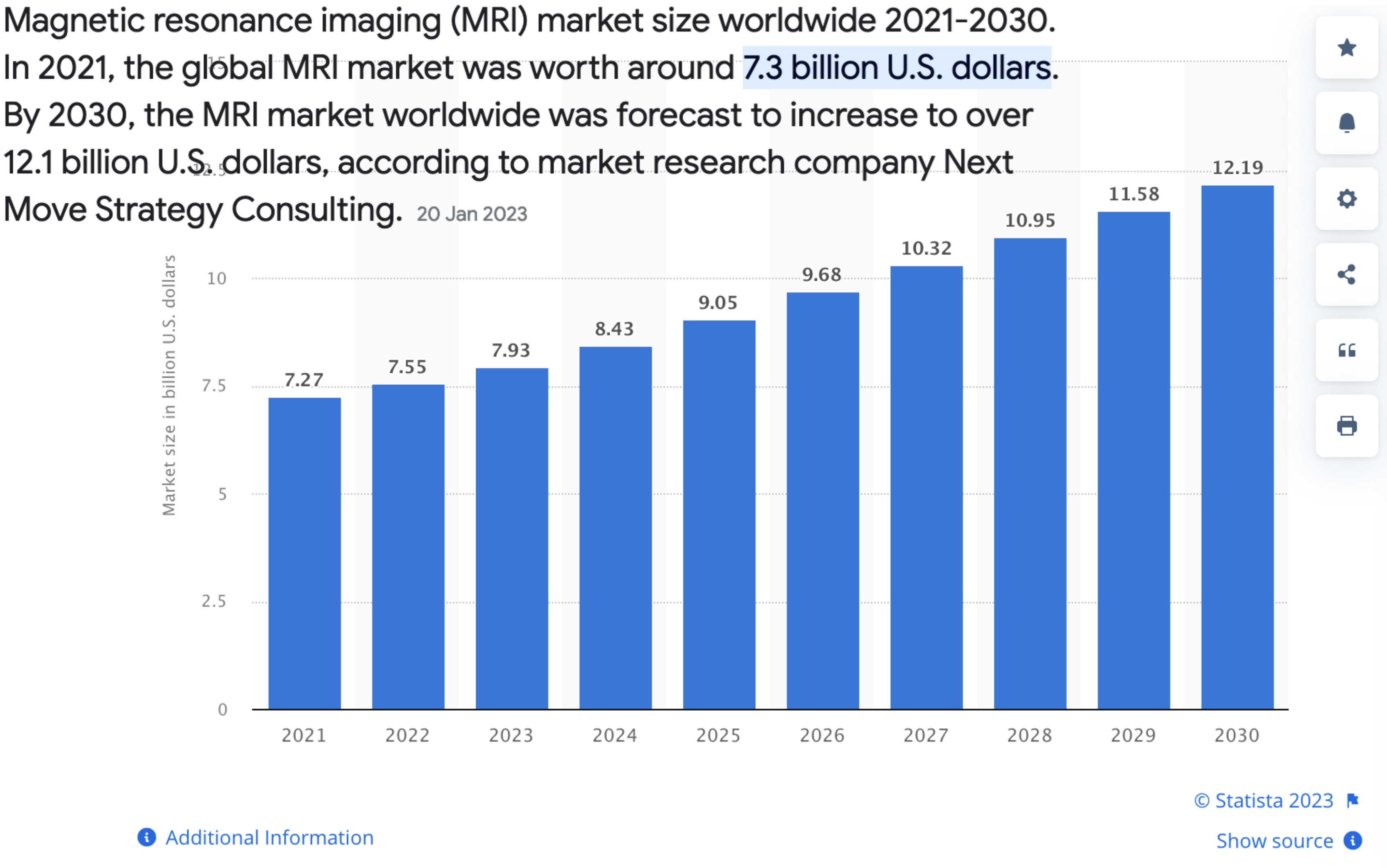
Outline

- HEP landscape
  - The need for high fields
  - The need for energy
  - The need for economics
- Case study: the Muon Collider
- HEP – For what ?
- Summary

Magnetic Resonance Imaging



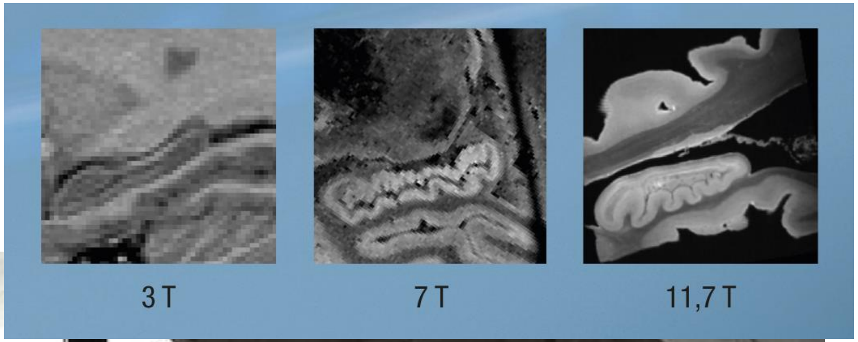
MRI Business



Magnetic resonance imaging (MRI) market size worldwide 2021-2030. In 2021, the global MRI market was worth around 7.3 billion U.S. dollars. By 2030, the MRI market worldwide was forecast to increase to over 12.1 billion U.S. dollars, according to market research company Next Move Strategy Consulting. 20 Jan 2023

Frontier of MRI

Example of images of the hippocampus taken at different MRI field



Head-only, 11.7 T MRI (Nb_3Sn)

Full-body, 11.7 T MRI (Nb-Ti)

Next step in MRI

Radboud Universiteit
SINCE 1923

Strongest MRI scanner in the world will be built in the Netherlands

20 February 2023 ▪ Research news item

A consortium of seven partners, led by the Donders Institute for Brain, Cognition and Behaviour (Radboud University), has received a €19 million Roadmap grant from NWO. It will be used to build the world's first MRI scanner with a magnetic field strength of 14 Tesla in Nijmegen.

HTS technology selected

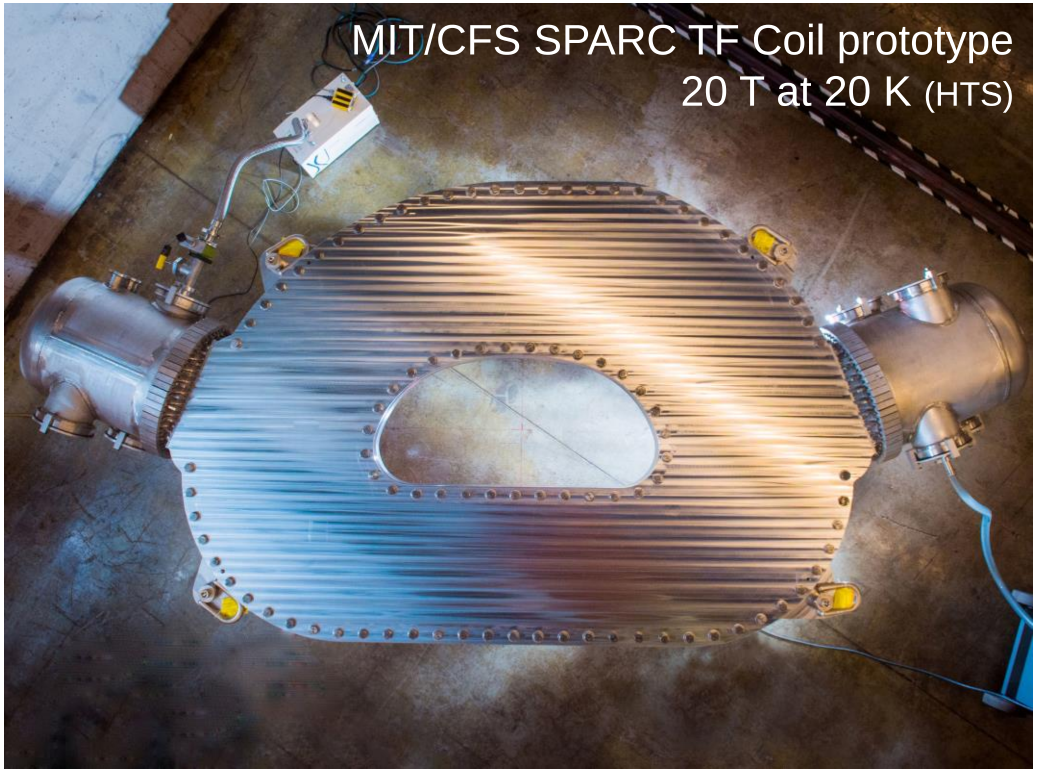
https://www.neoscan-solutions.com/_files/ugd/306bd8_8db80b639c064514ae31ea160a52adba.pdf

Radboud University (responsible institution), Amsterdam Medical Centre (AMC), Leiden University Medical Centre (LUMC), Maastricht University, Radboud University Medical Centre, Spinoza Centre for Neuroimaging – KNAW and University Medical Centre Utrecht (UMCU)

Thermonuclear fusion

ITER Central Solenoid Model Coil
13 T in 1.7 m (LTS)

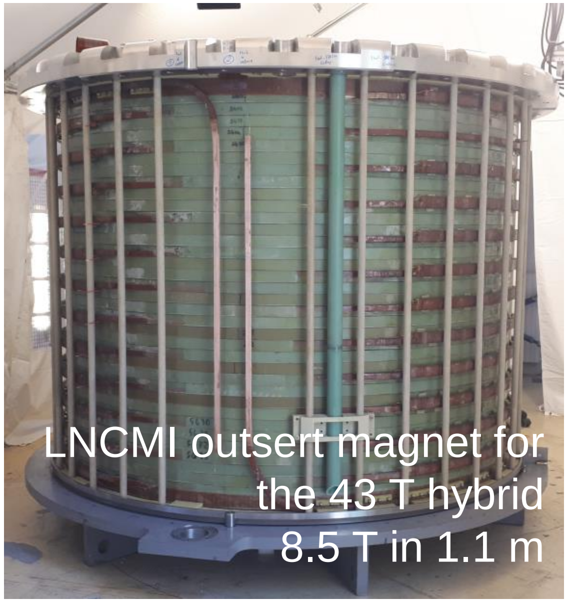
Present technology, LTS-based

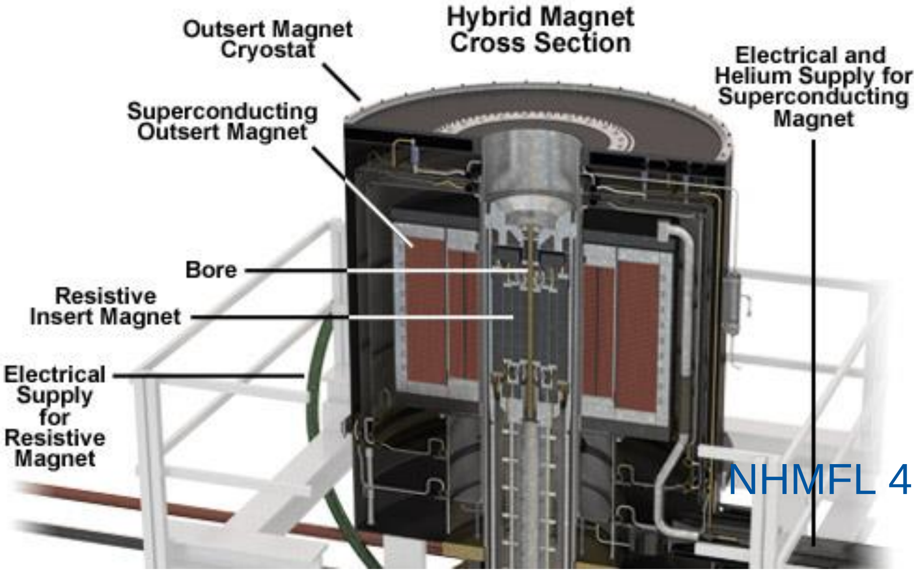


MIT/CFS SPARC TF Coil prototype
20 T at 20 K (HTS)

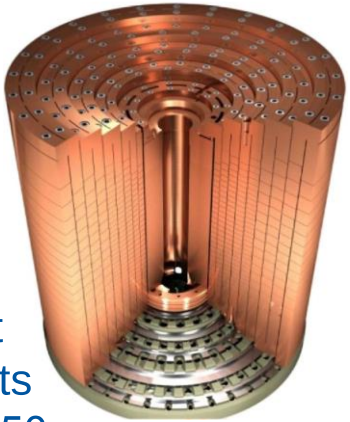
Compact fusion reactors, based on HTS

High Magnetic Field Science


LNCMI outsert magnet for the 43 T hybrid
8.5 T in 1.1 m

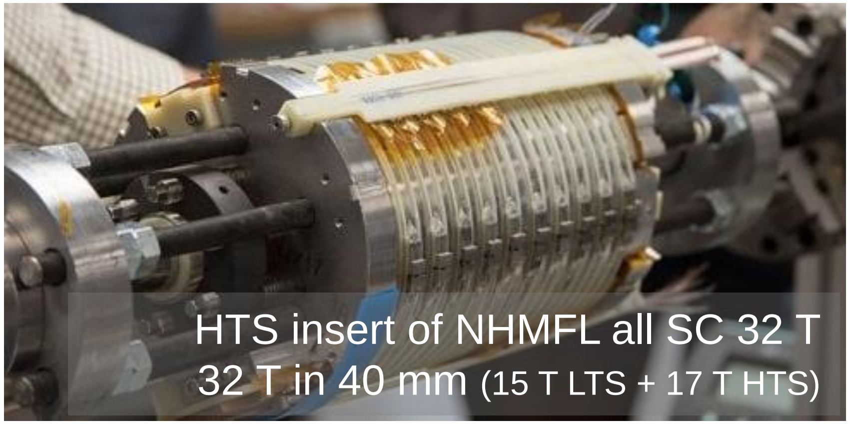


NHMFL 45 T hybrid

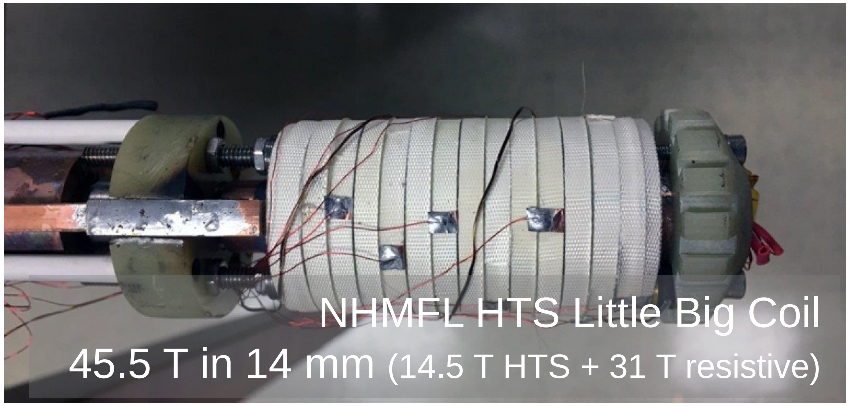

LNCMI resistive
(poly-helix) insert
for hybrid magnets
10…20 T in 30…50 mm


NHMFL series connected hybrid
36 T in

High Magnetic Field Science



HTS insert of NHMFL all SC 32 T
32 T in 40 mm (15 T LTS + 17 T HTS)

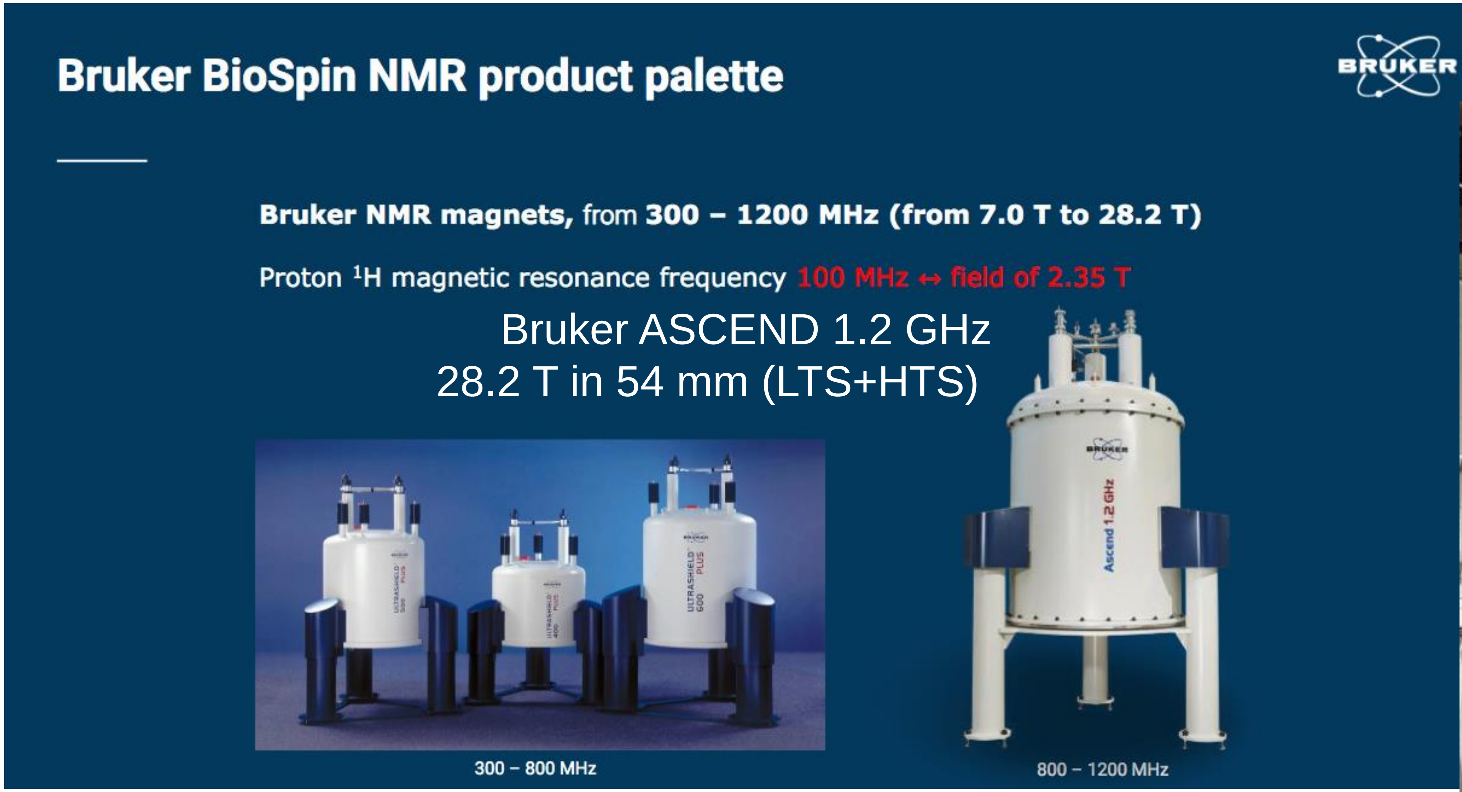


NHMFL HTS Little Big Coil
45.5 T in 14 mm (14.5 T HTS + 31 T resistive)

LNCMI/CEA Nougat
HTS insert
32.5 T in 50 mm
(12. 5 T HTS + 20 T resistive)

Sunam NI one-body
HTS magnet
26.4 T in 35 mm
(26.4 T HTS multi-width)

Nuclear Magnetic Resonance



Bruker BioSpin NMR product palette

Bruker NMR magnets, from **300 – 1200 MHz (from 7.0 T to 28.2 T)**

Proton ^{1}H magnetic resonance frequency 100 MHz ↔ field of 2.35 T

Bruker ASCEND 1.2 GHz
28.2 T in 54 mm (LTS+HTS)

300 – 800 MHz

800 – 1200 MHz

JEOL 1.02 GHz
24 T (LTS+HTS)

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Summary – 1/2

- The next step at the energy frontier of high energy physics needs
  - High fields (dipoles and quadrupoles from 16 T up to 20 T, solenoids from 20 T up to 40 T and more)
  - Energy efficiency (increase operating temperature to profit from Carnot, *minimal cryogen* usage)
  - Economics (high J_E, compact magnets, to reduce construction costs, sustainable Maintenance and Operation)
- This is not only useful to HEP, but also to other fields of science and societal applications

Summary – 2/2

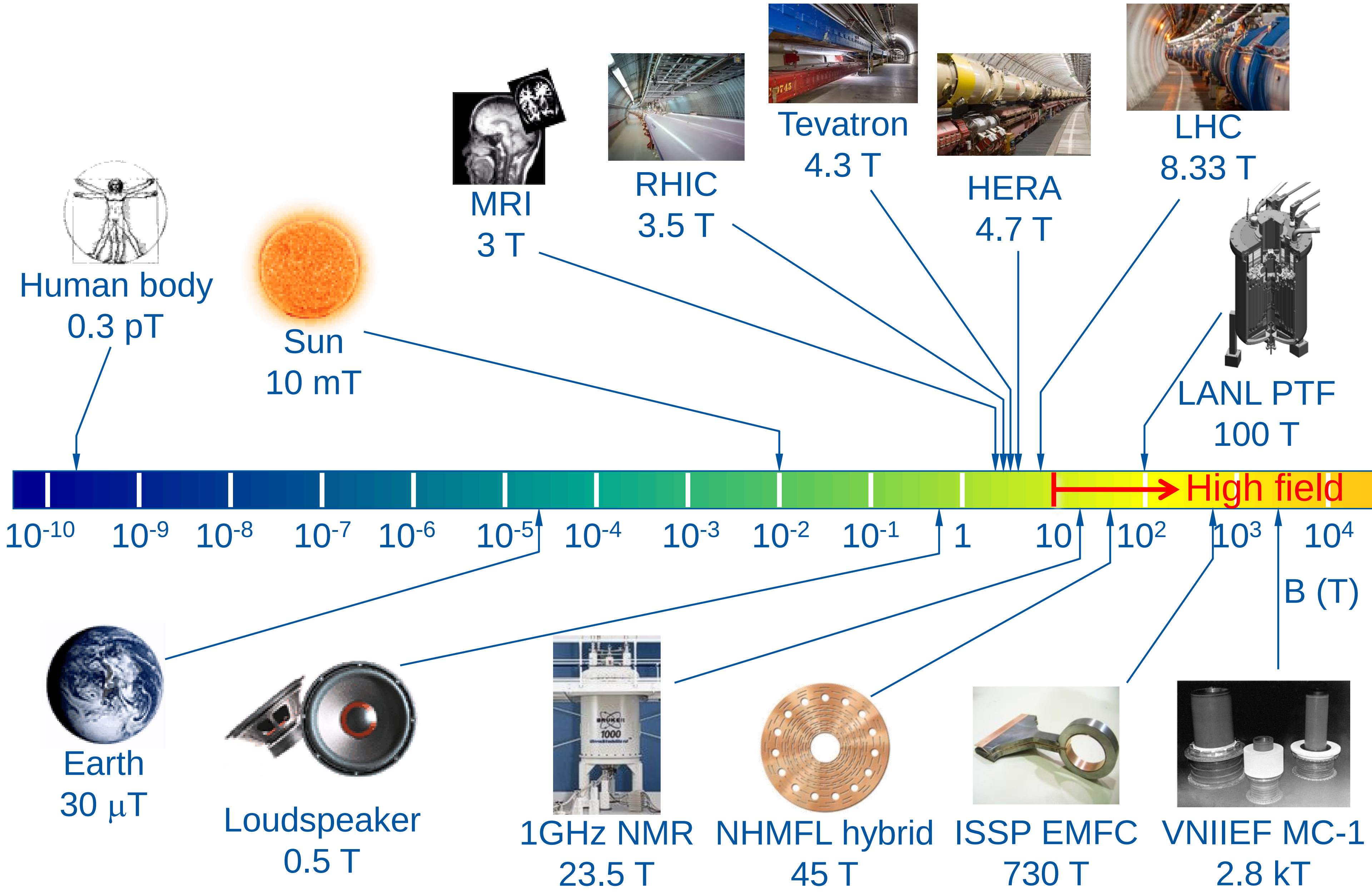
- Notes:
  1. HTS is the only path beyond 16 T
  2. HTS offers efficiency and sustainability
  3. HTS critical current density is not the limit
  4. HTS is ideally matched to NI technology
  5. HTS cost is decreasing fast !
  6. HTS may be THE enabler for the next collider

However…

There is a lot to be done
and this is why you are here !

Final quiz

Do you know what is the largest number of Tesla’s ever produced ?



Human body
0.3 pT

Sun
10 mT

MRI
3 T

RHIC
3.5 T

Tevatron
4.3 T

HERA
4.7 T

LHC
8.33 T

LANL PTF
100 T

High field

Earth
30 µT

Loudspeaker
0.5 T

1GHz NMR
23.5 T

NHMFL hybrid
45 T

ISSP EMFC
730 T

VNIIEF MC-1
2.8 kT

Magnetar found very close to the supermassive black hole, Sagittarius A*, at the center of the Milky Way

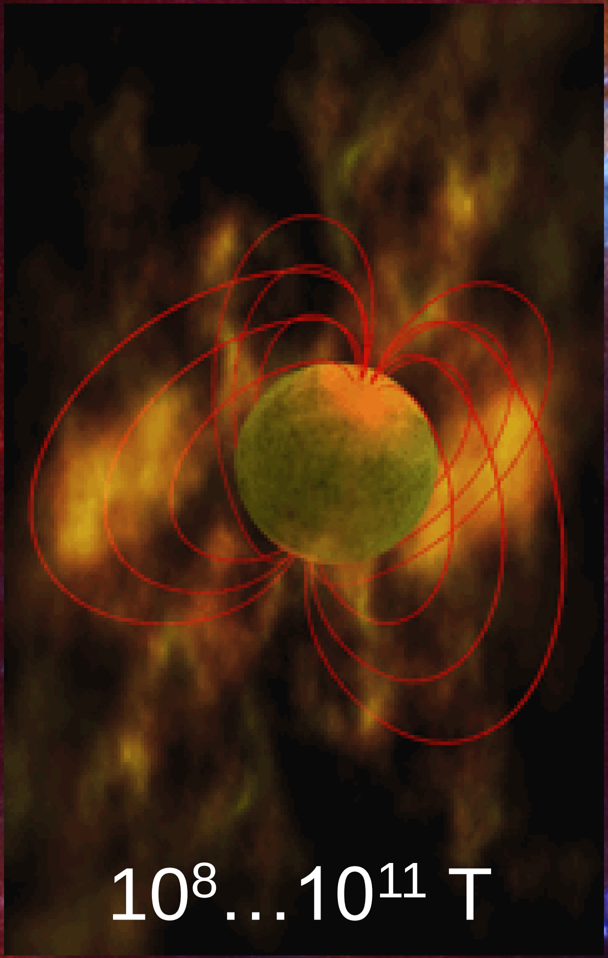
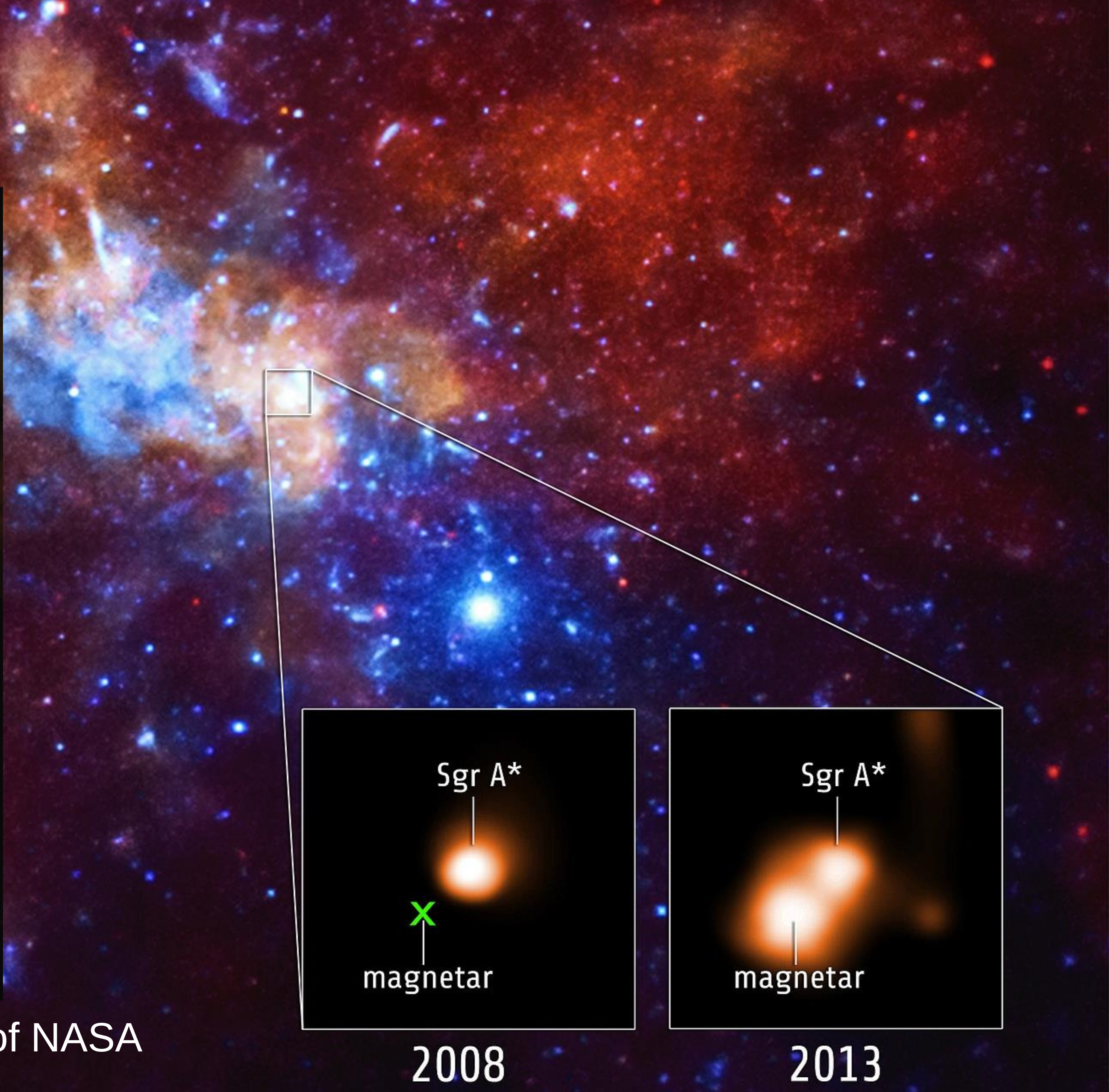
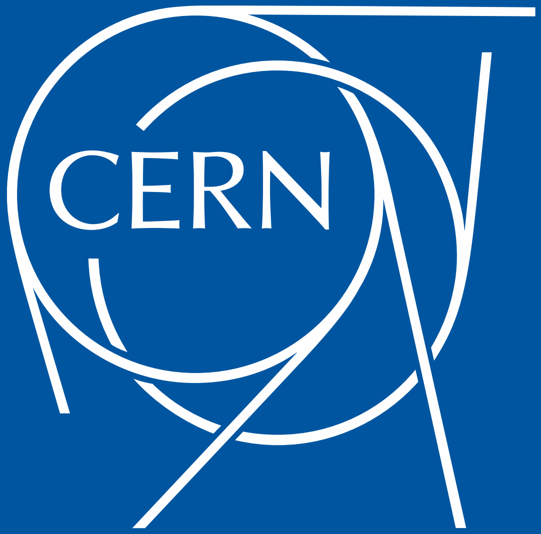


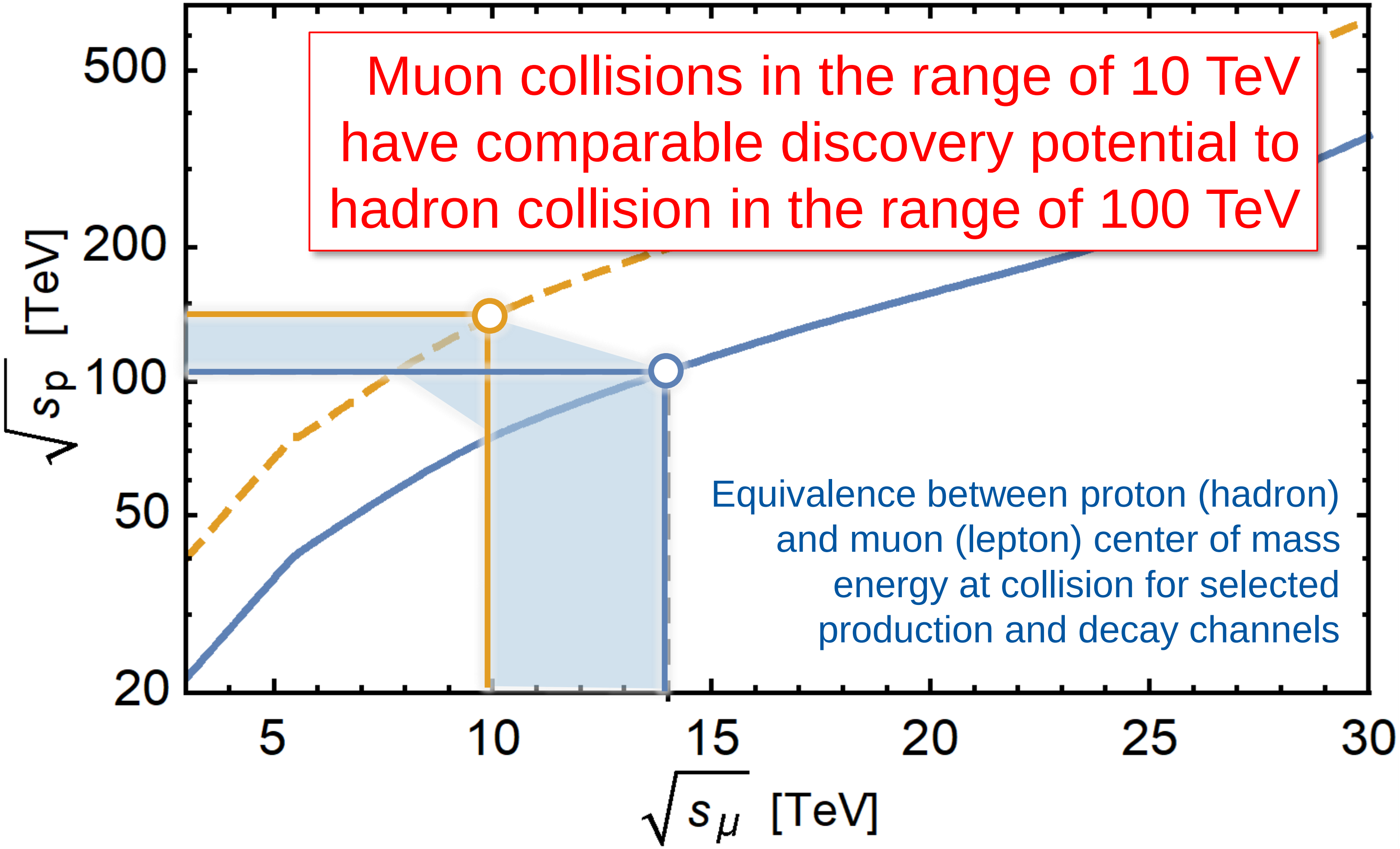
Image courtesy of NASA




CERN

Muon Collider: Physics ?

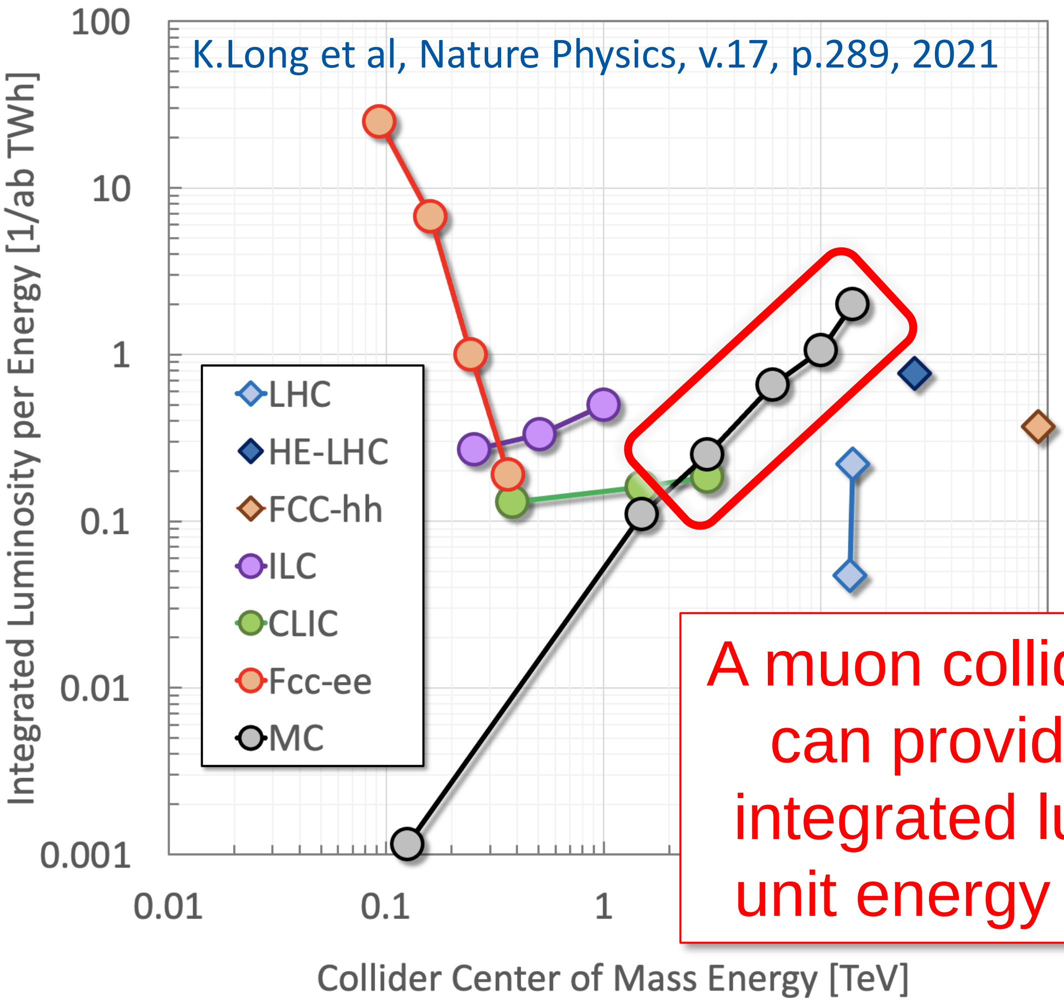
https://doi.org/10.48550/arXiv.2203.07261



Muon collisions in the range of 10 TeV have comparable discovery potential to hadron collision in the range of 100 TeV

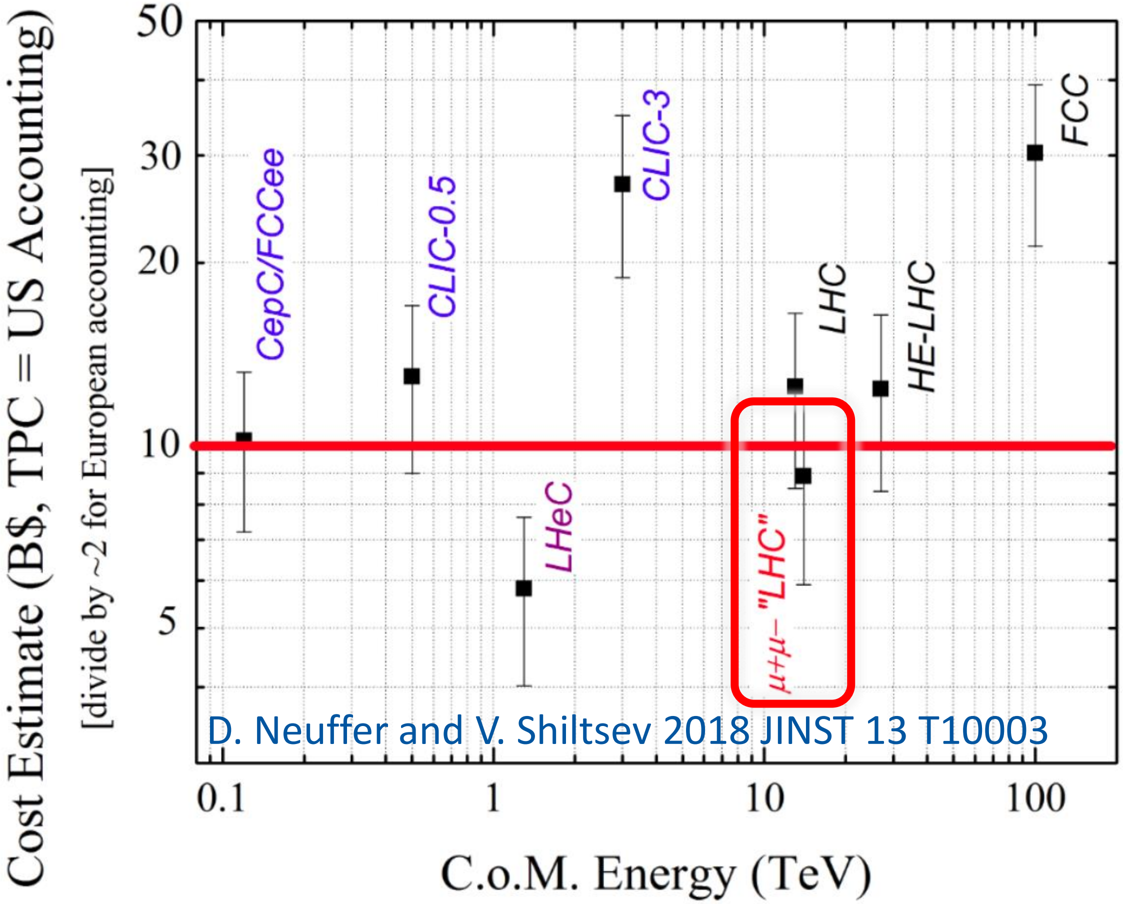
Equivalence between proton (hadron) and muon (lepton) center of mass energy at collision for selected production and decay channels

Muon Collider: Sustainable ?


K.Long et al, Nature Physics, v.17, p.289, 2021

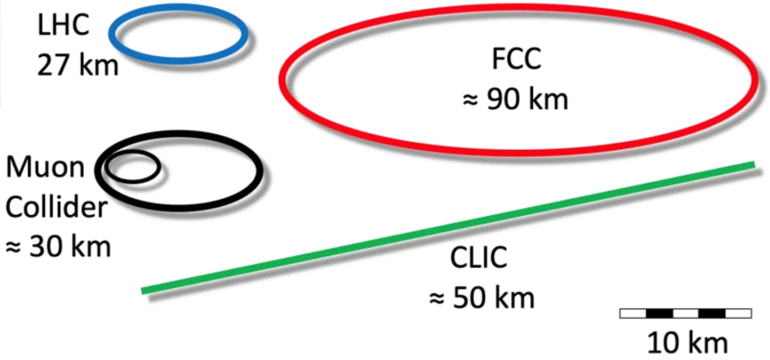
A muon collider at 10 TeV can provide the highest integrated luminosity per unit energy consumption

Muon Collider: Affordable ?

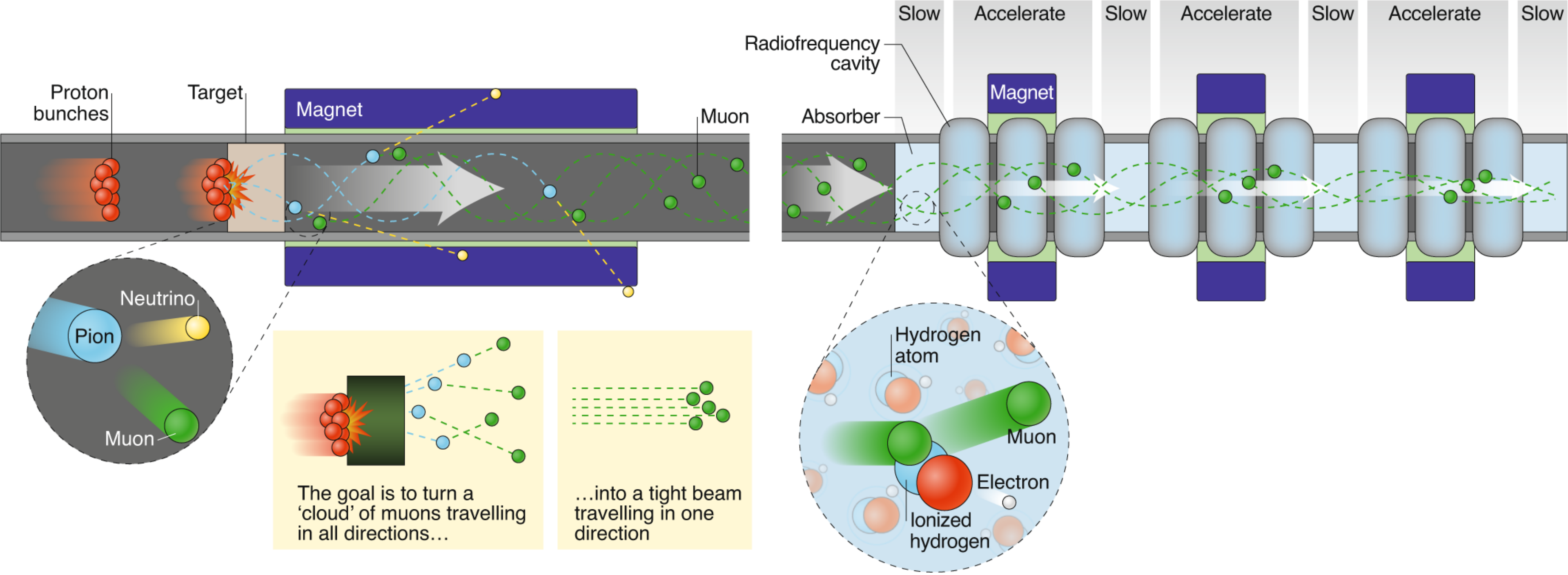


D. Neuffer and V. Shiltsev 2018 JINST 13 T10003

A 10 TeV muon collider profiting from the LHC infrastructure could be the most cost-effective energy frontier collider



Muon cooling



HFM Objectives (long term)